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PHOTOCELLS

AND THEIR APPLICATION

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BY

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PREFACE

THE photoelectric cell, *alias* photocell, *alias* phototube, has finally come into its own. Invented before the thermionic tube, the photocell has remained rather obscurely in the background of electrical achievements; but with the discovery that feeble photoelectric currents could be efficiently and faithfully amplified by means of the thermionic tube, the photocell has come out of obscurity into an active world of useful service. Even now one can find advertisements of commercial phototubes on the same pages with familiar radio tubes.

The layman has not yet gained a speaking acquaintance with the photocell. To him it is something quite novel and rather mysterious. Only in certain industrial and educational laboratories has the photocell been a common tool for many years. It is high time that the public in general should be introduced to the modern "electric eye" and be taught its normal characteristics and its special idiosyncrasies.

It has been the distinct aim of this book to do just that thing. The authors have attempted to assemble reliable information from the thousands of articles scattered throughout the world's literature, sift the significant from the inconsequential, and present the residue in the light of their own training and long experience with the subject. They have been aided in this task by consulting not only existing texts on photoelectricity in this country,

which are unfortunately of an older vintage, but also the more recent books on the subject by foreign writers.

It is believed that in the chapters following the reader will find an understandable account—not too technical for the untrained man and not too shallow for the specialist—an accurate account of the origin and rise of the photocell, its behavior, and its functioning as a real entity of affairs. It is hoped that the general reader of this book will acquire not only a complete background of information in photoelectricity but also a practical knowledge of the art of making photocells and of using them in electrical circuits for picture transmission, television, sound projection, and for many industrial applications.

Both the authors express their indebtedness to Westinghouse Electric and Manufacturing Company for courteous cooperation in the compilation of material and for providing facilities for research in photoelectrics and allied subjects. Thanks are also extended to their colleagues for valuable data and constructive suggestions. Obligations are acknowledged to numerous periodicals and other publications whose editors have kindly consented to the reproduction of specific material. Full credit is given in each instance.

V. K. Zworykin
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Westinghouse Research Laboratories,
East Pittsburgh, Pa.
May, 1930.

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PHOTOCELLS AND THEIR APPLICATION

CHAPTER I

HISTORICAL INTRODUCTION

The discovery of the *photoelectric effect* is an excellent illustration of scientific procedure and of human genius. Genius has been defined informally as the ability to detect the difference between "tweedle-dee" and "tweedle-dum"; while a familiar adage maintains that genius is the infinite capacity for taking pains. By either count Heinrich Herz may be classified as a genius, because he not only grasped the significance of an inappreciable change in an empirical phenomenon, but also patiently plodded through a tedious series of logical experiments to a successful judgment concerning the cause of that phenomenon.

Herz's discovery. It was in 1887 that Herz performed his classical experiments on the effect of electrical discharges in one oscillatory circuit upon another similar circuit not directly connected. Figure 1 is a modified sketch of the apparatus employed. A Ruhmkorff coil, *a*, empowered by a battery, *b*, of sixteen large Bunsen elements, and provided with a special mercury interrupter, *c*, caused vigorous sparks to jump the gap, *d*. A second smaller spark coil, *e*, produced sparks about 1 mm. in length to bridge the gap in a Riess spark

micrometer, f. The original experiments consisted in varying parameters of the first, or inducting, circuit and measuring the effect on the length of the spark in the micrometer gap. After setting down the numerical results in his article[1]* describing the experiments, he concludes with this remarkable paragraph:

> In order to make possible a repetition of this investigation with the same results, I must add another statement whose significance might not seem clear at first. In all of the experiments described, the apparatus was arranged so that the spark of the inductor was visible from the position of the spark at the micrometer gap. If this condition was altered, the same qualitative results were obtained, but the lengths of the secondary sparks appeared to be decreased. I have given special study to this phenomenon and intend to publish my findings in a separate paper.

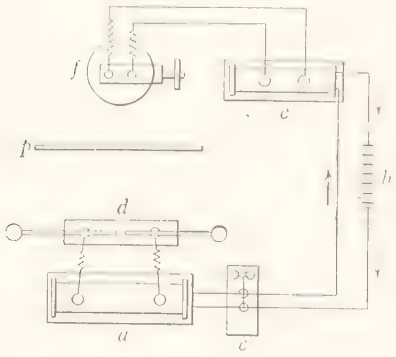

FIG. 1.—Herz's classical apparatus with which the photoelectric effect was first observed.

This observation of the difference in length of the secondary spark when the parent spark was in sight and when it was not, was the detection of the difference between "tweedle-dee" and "tweedle-dum".

The paper to which Herz referred appeared the same year.[2] By reference to Fig. 1 we can follow his analysis. In order to make more visible the feeble sparks that occurred at the micrometer gap, Herz built a little box about this measuring device. He noted that there seemed to be a consistent decrease in the maximum

* See references at end of chapter.

length of the sparks. The effect was not due to electrostatic or electromagnetic shielding, because the box was made of non-conducting material. By removing separately different sides of the box he discovered that only the side which obstructed the view to the inductor spark produced any difference, and soon determined that some sort of radiation which traveled in straight lines from the inductor spark was responsible for the effect. If the light from this spark was reflected by means of a polished plate of metal upon the micrometer gap, while direct radiation was screened, the maximum length of the secondary spark increased as before. And yet, if the mirror was removed and only a clear plate of glass was used as a shield, the effect ceased. By interposing numerous opaque and transparent solids and liquids, he definitely established that the effect appeared in proportion to the ability of the interposed shield to transmit ultra-violet radiation. To clinch this result, he placed a vertical slit before the inductor spark and dispersed the light coming through the slit by means of a large quartz prism. Upon passing the micrometer gap through the prismatic spectrum from the red and to the violet region, the effect appeared only when the micrometer spheres reached the region beyond the visible light in the near ultra-violet.

Thus Herz concluded that *ultra-violet radiation from one spark gap could make easier the passage of sparks across a second gap.* He demonstrated in addition by similar methods that ultra-violet light from other sources such as an arc or a magnesium flare is just as effective as a spark; that the radiation seems to have greatest effect when incident upon the negative terminal of a gap; that a large sphere or plate terminal serves

better than a small pointed one; and that freshly polished surfaces are highly superior to tarnished ones.

Herz's investigation, only in briefest possible outline above, pictures his infinite capacity for taking pains. Certainly to him belongs the credit of discovering the photoelectric effect and of initiating research on a new phenomenon which has since become of such scientific interest and commercial value. But he did not pursue the subject further. At the close of this second article he remarks: "For the present I limit myself to the presentation of these established facts without attempting to advance a theory on how such observed phenomena could occur."

It is proper to add here that during the following year E. Wiedemann and H. Ebert [3] jointly confirmed Herz's results by a modification of his method and apparatus, especially with respect to the activity being confined altogether at the negative terminal of the irradiated gap.

The Hallwachs effect.—Wilhelm Hallwachs [4] felt that there must a fundamental effect due to irradiation of materials by ultra-violet light which should be independent of spark gaps and electrical oscillatory discharges. Therefore he set himself the task in 1888 of simplifying Herz's apparatus and method of procedure. He insulated a polished zinc sphere and connected it electrically to a gold-leaf electroscope. This insulated system he charged negatively until the leaves showed a wide divergence. When the sphere was illuminated by light from an arc, the leaves quickly collapsed, showing that the sphere had lost its negative charge. This could be repeated an indefinite number of times; but if the system was charged positively, the irradiation by the

are had no appreciable effect. Later also he established that a neutral insulated system will acquire a positive charge under the incidence of ultra-violet light.

Hallwachs observed the important fact that a positively charged insulated body will lose its charge when placed in the neighborhood of a negatively charged body which is being irradiated. After further research, he definitely concluded that *under influence of ultra-violet light negative electricity leaves a body and follows electrostatic lines of force*. This phenomenon is referred to as the *Hallwachs effect.*

During this same year two other investigators contributed materially to the quantitative study of the Hallwachs effect which was now exciting so much interest among scientific men. One of these investigators, Righi,[5] set up a polished plate with a coarse mesh grid before it. The plate was connected to one pair of quadrants of an electrometer, while the grid was connected to the other pair and to ground as indicated in Fig. 2. When the plate received light from a source through the grid, the electrometer registered a definite deflection, and the grid and plate came to the same potential. He judged that the deflection was a measure of the original potential difference between plate and grid, their "contact potential". Later developments reveal that his conclusion is not true in general. But he showed that such an arrangement is capable of pro-

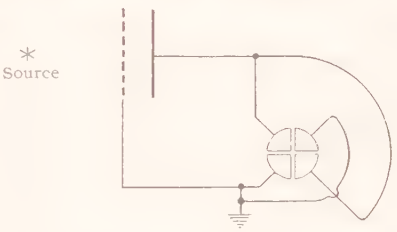

FIG. 2.—The circuit employed by Righi to measure the charge acquired by a photosensitive body.

ducing a current under the action of light and termed it a *photoelectric cell.* The name has clung even to widely modified devices which are not at all employed as current generators. Righi put two similar cells in series and found that when both were illuminated the deflection of the electrometer was doubled. This constituted a photoelectric battery.

The second investigator was Stoletow.[6] He also employed a polished plate in conjunction with a grid, but, in place of an electrometer, used a high-resistance galvanometer, and in addition introduced an external electromotive force consisting of a Voltaic pile, as outlined in Fig. 3. In this arrangement, radiation on the plate permitted a continuous small current to flow from grid to plate in the positive sense. Stoletow approached more recent methods for measuring photoelectric effects.

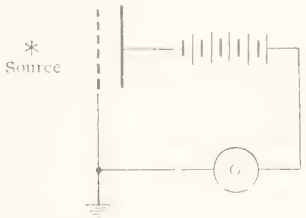

FIG. 3.—The circuit employed by Stoletow to measure photoelectric currents.

The alkali metals. The next great advancement in the art of photoelectrics was made by the two famous co-workers, Julius Elster and Hans Geitel. It had been observed by them that, of all the metals heretofore studied for photoelectric sensitivity, aluminum, magnesium and zinc appeared to give best results. They reasoned that since these metals were all electropositive, chemically speaking, it would seem reasonable to expect at least as good results from metals which are more electropositive than the ones named. They proceeded therefore to investigate the alkali metals, particularly

sodium and *potassium*. Unfortunately these highly active elements almost instantly react with air and water vapor to form oxides and hydroxides which were found to be relatively insensitive. Having previously made the discovery that an *amalgam of zinc* could be employed with much better satisfaction than zinc alone, it occurred to Elster and Geitel[2] in 1889 that perhaps the alkali elements could be handled in a similar manner. After much preliminary experimentation they arrived at the happy result that a fresh dilute amalgam of either sodium or potassium was many times more sensitive than even amalgamated zinc. The following table taken from their original paper will give an indication of the quantitative measurements made on the relative rates of discharge by weak daylight of a negatively charged system consecutively connected to the various amalgams. V_0 is the voltage to which the system was originally charged; V is the residual voltage after an exposure of t seconds to radiation.

	V_0 (volts)	V_t (volts)	t (seconds)
1. Pure Hg	185	175	30
2. Hg + Zn	195	116	15
3. Hg + Na	195	0	10
4. Hg + K	195	0	5

Even more significant than the relatively high sensitivity of the alkali amalgams was the fact that even light which had passed through a plate of glass could still affect these new surfaces and discharge them rapidly. This meant that *sodium and potassium were photoelectrically active to ordinary visible radiation!*

The next year Elster and Geitel described in detail the manufacture of a sodium amalgam photoelectric cell entirely enclosed in glass and well evacuated (see Fig. 4). They remark: "As may be judged from the description, no provision has been made to admit light of short wavelength. A window of quartz or similar material is not necessary, as light transmitted by the glass proves to be sufficient."

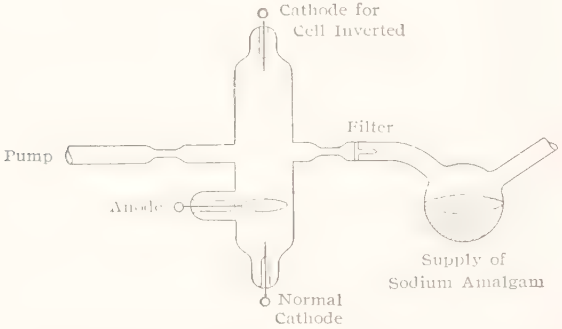

FIG. 4.—The sodium-amalgam photoelectric cell developed by Elster and Geitel.

The photoelectric carrier. - We have seen that Hallwachs proved that the photoelectric effect comprised the liberation of negative electricity which followed electrostatic lines of force. Now Elster and Geitel, in continuing their active research, made a remarkable discovery of theoretically fundamental importance, providing as it did a new clue to the nature of the phenomenon first observed by Herz.

To appreciate the sense of their work, we should familiarize ourselves with a type of electrical discharge that occurs in a *Geissler tube*, which consists essentially of a glass tube provided with two electrodes and con-

taining a gas at low pressure. If the pressure is sufficiently low and a high voltage is impressed across the electrodes, an electric beam proceeds in straight lines from the cathode and strikes against the opposite walls and parts of the tube. This beam was found to be capable of being deflected by either a magnetic or an electrostatic field; hence it must consist of *electrically charged particles possessing a definite inertial mass.* The direction of the deflection indicated that the particles were *negative.* J. J. Thomson, by measuring resultant deflections after such a beam had passed through crossed magnetic and electrostatic fields, was able to calculate the ratio of the charge of one of the particles to its mass.[9] By an independent experiment he also measured roughly the amount of charge on each particle. It finally turned out that the mass was less than one thousandth that of a hydrogen atom, the lightest of all elements. This newly found subdivision of matter has been subsequently called an *electron.* Thomson noted that electrons from all sorts of metal cathodes were identical in charge and in mass.

It occurred to Elster and Geitel that if a tube containing a photoelectric substance were well evacuated, it might be possible to influence the flow of negative electricity from the surface of the cathode by means of a magnetic field. Actual observations[10] revealed that the photoelectric current could be reduced as much as 50 per cent when the field was applied in a direction at right angles to the path between cathode and anode. Surely then *the photoelectric carrier must be a negatively charged particle.* It might be an electron just as in the cathode beam or it might be a negatively charged atom from the cathode itself. To settle this point, P. Lenard[11]

made up a photoelectric cell with a platinum wire for anode and sodium amalgam for sensitive cathode. He illuminated the surface long enough to permit 2.9×10^{-4} coulomb of electricity to flow, calculating that if the carrier was the sodium atom there should be deposited on the anode about 0.7×10^{-4} milligram of sodium. Although half that amount could be definitely detected by a Bunsen flame test, there was not the slightest trace of alkali detectable on the wire. As a more positive proof, he made use of a special structure such

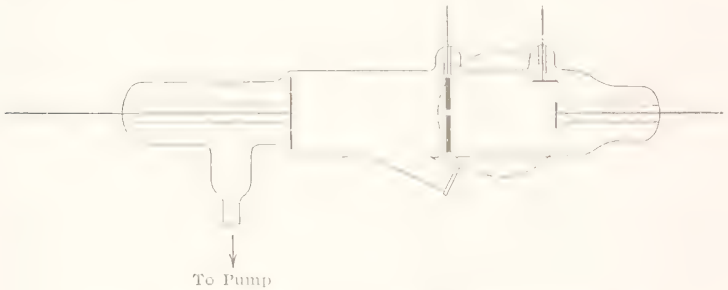

FIG. 5.—Lenard's experimental tube with which he measured the ratio e/m for the photoelectric carrier.

as is shown in Fig. 5. Photoelectric particles released from an aluminum cathode by ultra-violet light are drawn to a centrally perforated anode and a portion of them pass through the aperture to a terminal at the opposite end, but when a magnetic field of the proper sense and strength is applied perpendicular to the plane of the sketch, the electric stream is bent upward to a second extra terminal. Quantitative measurements yielded a result for ratio of charge to mass substantially the same as that found by Thomson for the electrons.

More accurate measurements made by Merritt and Stewart[14] in 1900 and especially by Alberti[15] in 1912

prove beyond question that the *photoelectric carrier is indeed the negative electron.* The most recently accepted values for constants of the electron are:

$$\begin{aligned} e/m &= 1.77 \times 10^{7} \text{ e.m.u. per gram} \\ e &= 1.59 \times 10^{-10} \text{ e.s.u.} \\ &\quad 1.59 \times 10^{-19} \text{ coulomb.} \\ m &= 8.98 \times 10^{-28} \text{ gram.} \end{aligned}$$

Empirical laws. Out of the experimental work of the early investigators there gradually crystallized two fundamental laws of photoelectric action, their statement developing from crude approximation to confident precision as more and more accurate research eliminated disturbing errors which confused preliminary results. The *First Law* may be worded:

The number of electrons released per unit time at a photoelectric surface is directly proportional to the intensity of the incident light.

This law has been rigorously tested for a range of intensities varying from zero to full sunlight. Wherever deviations have been reported, the discrepancy could always be accounted for by errors in measurement or by inherent faults within the cell employed which tended to introduce spurious currents or to hinder the total number of electrons actually released by radiation from being collected.

The *Second Law* is one of a more surprising nature.

The maximum energy of electrons released at a photoelectric surface is independent of the intensity of the incident light, but is directly proportional to the frequency of the light.

This statement implies that when electrons are emitted under influence of radiation they possess various

velocities, but that there is a definite highest velocity which is determined by the greatest frequency of the radiation; and no matter how intense the same kind of radiation may become, this highest velocity will not increase!

Both of these laws really had their distinct origin in the experiments of Lenard. When they are considered together, one's concept of the action of light probably receives a jolt. As far as the photoelectric phenomenon is concerned, one is not to regard a glaringly intense beam of light as essentially more violent in its action than a dimly visible beam of the same kind of light; but rather to regard the more intense as simply operating upon a larger number of objects per unit area of illuminated surface.

The underlying theory of the laws will be presented in the next chapter.

The first practical cells. One of the first observations made by the early workers was that only fresh surfaces appeared to be active under ultra-violet irradiation, and that such surfaces very rapidly tarnished and became unresponsive. Thus no practical use of the photoelectric effect could be made for satisfactory photometric or similar measurements. Perhaps the first photometric device was that originated by Elster and Geitel in 1889.[1] Their amalgamated zinc sphere remained constant in action over periods sufficiently long for a series of comparison readings and could be easily restored by new amalgamation. However, their sodium amalgam enclosed in an evacuated glass vessel constituted the first structure worthy of the name photoelectric cell. Even in this cell, the cathode surface had to be renewed occasionally by a crude filtering process.

It had the distinct advantage of being sensitive to visible light.

In 1904 Hallwachs [14] devised a cell for photometric purposes consisting of an evacuated container with a copper plate coated with black oxide for cathode. It was found to be constant over a period of several months, but was not sensitive to visible radiations.

Elster and Geitel continued to improve the alkali cell. They first found that the *hydride crystals* of sodium and potassium were more sensitive than the metals themselves. Then they struck upon a sensitizing process which marked a new era of development. By passing a glow discharge through hydrogen gas in an alkali cell, the cathode surface was transformed into a *colloidal state* accompanied by high coloration and became as much as one hundred times more sensitive than the pure element. Thus, at least by 1912, they had increased the sensitivity of their early cells by two whole orders of magnitude.[17] Many cells manufactured today differ but little from the original hydrogenated alkali cells of Elster and Geitel.

How the sensitivity has been recently raised through two more orders of magnitude remains to be related in another chapter.

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CHAPTER II

GENERAL THEORY

I. RADIANT ENERGY

It is impossible to have clear notions concerning the photoelectric effect without understanding certain fundamental characteristics of *radiation* and of the *sources of radiant energy*. We begin by defining radiant energy as the energy associated with electromagnetic oscillations propagated through space. These oscillations may have frequencies varying from almost zero to inconceivably high values. The range of frequencies included in any given type of radiation determines its effect upon matter by which it is reflected, absorbed or transmitted.

Spectrum of radiant energy.—Figure 6 pictures the classification of radiation according to ranges of frequency and to its normal means of detection. It is notable that the octave of frequencies which constitutes *visible light* forms but the tiniest fraction of the entire gamut. The range of visible radiations is of course limited by the sensibility of the human eye. A frequency of approximately 750 thousand billion vibrations per second produces the sensation of violet color when incident upon the retina. Radiation of about half that frequency produces the sensation of red.

Radiations immediately beyond the violet constitue the *ultra-violet*. By use of a vacuum spark spectro-

Fig. 6.—A chart of the entire spectrum of radiant energy. There are no sharp boundaries between adjacent regions, but the limits drawn are those determined by empirical data available when the chart was prepared.

graph Millikan and Bowen [16] have been able to detect ultra-violet waves as short as 1.36×10^{-6} cm. Since the human eye may be considered as just failing to detect radiations beyond 3.80×10^{-6} cm., we may conclude that ultra-violet radiations occupy about 3 octaves of frequency. The simple relation between frequency and wavelength is $\nu = c/\lambda$, where c is the velocity of light taken very nearly as 3×10^{10} cm. per second.

It must be emphasized that all types of radiant energy differ from one another only in frequency or wavelength. Thus it is seen from Fig. 6 that most of the consecutive ranges overlap to a greater or smaller extent.

Osgood [17] has succeeded in detecting and recording long *X-ray* waves of lengths at least as great as 1.67×10^{-6} cm. On the other extreme, characteristic X-rays from the heaviest element, uranium, have been produced and measured by Dessauer and Back.[18] The shortest of these waves

is only 1.04×10^{-9} cm. Continuous X-rays may be produced by the bombardment of any kind of cathode by means of electrons under the accelerating influence of an electrostatic field. Duane and Hunt [18] have found that the equation $\nu \cdot \lambda = 12.35V$ may be used for calculating precisely the shortest wavelength (in centimeters $\times 10^{-8}$) that can be caused to radiate due to electronic bombardment under a potential of V kilovolts. X-ray tubes have been made which operate continuously at 500 kilovolts. By the formula, the shortest radiations must have a wavelength of only about 2.4×10^{-10} cm.

The so-called *γ-rays* emitted by radioactive materials are the next higher frequencies. From a rather complete table of γ-rays [20] we find the extremes of wavelengths to be 5.57×10^{-11} cm. and 3.90×10^{-9} cm. Thus "soft" γ-rays merge into the region of "hard" X-rays.

As far as the writer's information extends, no radioactive radiations have been measured with certainty which have wavelengths nearly as short as those of the *cosmic radiations* discovered by Hess. From measurements of the absorption coefficients of these celestial oscillations, Millikan and Cameron [21] deduce that the range of corresponding wavelengths lies between about 8×10^{-13} cm. and 5.25×10^{-12} cm. Consequently the highest radiant frequencies of which we have any knowledge whatsoever belong to the cosmic rays.*

Immediately on the opposite side of the visible region lies the *infra-red*. The human eye generally

* Recent experiments by Bothe and Kohlhörster and by L. F. Curtiss indicate that cosmic radiations may be of a corpuscular nature, possibly consisting of high-speed electrons. (Phys. Rev., 34, 1391, 1929.)

ceases to register below about 7.6×10^{-6} cm. Almost 20 years ago Rubens and Von Bayer [22] by a method of focal isolation detected infra-red radiations as long as 3.2×10^{-4} cm., but this limit has been advanced with considerable certainty by Nichols and Tear [23] to at least 4.20×10^{-4} cm. These investigators separated the long waves from a mercury arc by transmission through a thick plate of quartz and several layers of black paper.

The same men succeeded in generating and receiving *damped radio waves* only 2.2×10^{-2} cm. in length, or shorter than the long infra-red. But recently their results have been bettered by Arkadiewa,[24] who obtained damped oscillations of the unbelievably short length 8.2×10^{-3} cm. The shortest *continuous radio waves* capable of modulation (10 to 20 cm.) that have been generated were produced by a special oscillator made by M. G. A. Beauvais.[25] These waves have been received at a distance of 6 miles. Perhaps the longest radio waves are sent out by the Lafayette broadcasting station near Bordeaux, France. The wavelength is 22.5 kilometers or 2.25×10^{7} cm. However, any oscillation of electricity in a circuit, no matter how slow the frequency, is capable of radiating electromagnetic energy into space. Thus there is no actual limit to the length of radiant waves. Usually, we think of frequencies lower than those of the broadcast range as being simply associated with alternating or pulsating currents.

Sources of radiant energy. The range of radiant frequencies which normally produce emission of electrons begins in the near infra-red and extends to the upper limit. In ordinary usage, however, frequencies beyond the near ultra-violet do not come into play.

We are interested here only in sources capable of emitting the common range of photoelectric radiation. Such sources may be divided into two general classes, according to their physical state.

The first class consists of *incandescent gases* and *vapors*. These all emit radiations comprising discrete groups of frequencies, each group being so exceedingly narrow that it is practically one definite frequency. When a fine slit illuminated with such light is viewed through a prism which separates the groups, each one appears as a colored image of the slit. The frequencies corresponding to each image or line bear definite quantitative relations to one another and compose a definite system. Each kind of gas and vapor has its own peculiar system of lines.

Gaseous sources may be made luminous either by thermal or, more commonly, by electric excitation. An important example of incandescent gas is the *neon tube*, now playing such an important role in commercial sign lighting and in television. This rare gas, excited by an applied voltage, emits radiations consisting principally of an enormous number of red lines. The *mercury arc lamp*, frequently employed in photography, illustrates an incandescent vapor, rich in ultra-violet which is highly actinic. In the visible regions it radiates chiefly a very intense green line with several other lines of different colors.

The second class of sources comprises *incandescent liquids* and *solids*. These do not generally emit distinct lines, but rather the radiation consists of an infinite number of frequencies. However, all such frequencies always begin in the deep infra-red and end either in the visible or the near ultra-violet. If the slit is illumined

TABLE 1

TEMPERATURE, BRIGHTNESS AND EFFICIENCY OF SELECTED SOURCES OF ILLUMINATION

(International Critical Tables)

T, T_B, T_C = true, brightness, and color temperature in degrees Kelvin;
E = efficiency in lumens per watt;
B = intrinsic brightness in candles per cm.^{2}

Source	T	T_B	T_C	E	B	Remarks
Candle, sperm	.....	.....	1930	.....	1.0	Bright spot
Kerosene: flat	.....	1500	2055	.....	1.2	Bright spot
Hefner lamp	.....	.....	1880	.....	0.7	Bright spot
Pentane lamp	.....	.....	1920	.....	.....	10 cp. std.
Gas: flame	.....	.....	2160	.....	.....	Batswing
Mantle	.....	.....	.....	.....	6.2	Bright spot
Vacuum lamps:						
C, 50 W	2130	.....	2195	4.0	78.0	Treated
Ta, 50-W	2180	.....	2260	6.3	53.0	
W, 60-W	2465	.....	2509	10.1	211.0	
Gas-filled lamps:						
W, 50-W	2685	.....	2670	10.0	469.0	
1000-W	3185	.....	3175	24.2	2065.0	Stereopticon
Bulb frosted on inside:						
W, 50-W	2650	.....	.....	10.0	7.8	Coiled
Electric arc:						
Solid C	.....	3385	3780	.....	9200.0	
Cored C	.....	3075	3420	.....	4130.0	
Hg, 500-W	.....	.....	.....	.....	350.0	Quartz, 100v.
Clear sky	.....	.....	.....	.....	0.8	Average
Moon	.....	.....	.....	.....	0.25	Bright spot
Sun	.....	.....	.....	.....	165,000	Surface of earth
					224,000	Above atmosphere

by this type of radiation, the contiguous prismatic images would overlap to produce a continuous spectrum.

The postive crater of a *carbon arc* is perhaps the most intense solid source devised. It is used in the projection of motion pictures and in searchlights. A more important source is the *tungsten filament electric lamp.* The amount of continuous energy from it may be accurately controlled so that it is of great service where steady brilliant illumination is desired. It is indispensable as a source for the photocell in the sound equipment for talking pictures.

Black body radiation. A black body may be defined as an ideal material object which is capable of absorbing or emitting all frequencies of radiation. A surface covered with a dead black coating, such as a flat paint or better a layer of soot, approaches the ideal fairly well. Practically perfect black body conditions are obtained by use of a cavity entirely enclosed except for a minute aperture through the enveloping walls. Any radiation which finds its way into the cavity has an infinitesimally small chance of ever emerging again, and hence the device serves as a perfect absorber. Since Kirchoff has proved that all bodies possess the same power of emission as of absorption, the cavity must also be a perfect radiator from the interior out through the aperture.

If a body has its temperature increased, the amount of radiation from it increases much more rapidly in proportion than the temperature. Upon analyzing empirical measurements for incandescent platinum, Stefan[2] proposed that the total radiation from a body is directly proportional to the fourth power of the absolute temperature; that is,

$$E = kT^4$$

where k is a constant. This law was verified by Lummer and Pringsheim by use of the radiating cavity.

As early as 1899 Lummer and Pringsheim [27] had plotted for various temperatures of a black body the amount of energy radiated with a given frequency, and found that there is always a definite frequency for each temperature at which the radiation is a maximum. Figure 7 shows a family of such curves for a black body. Observe in Fig. 7*a* that, as the temperature increases, the frequency of maximum emission moves progressively toward higher values. It was discovered by Wien [28] that the wavelength corresponding to the frequency of maximum emission is related accurately to the absolute temperature by the relation

$$\lambda_m T = C$$

where again C is a constant, later evaluated as 0.294 cm.-deg. This equation is familiarly known as *Wien's displacement law.*

Many attempts had been made to find a theoretical equation which would accurately fit the experimental curves shown in Fig. 7 described as spectral energy distribution curves. One formula, due to Wien,[29] stated that

$$E = a\lambda^{-5} e^{-b/\lambda T}$$

in which E represents the energy radiated with wavelength λ at a temperature T degrees absolute, a and b being constants. This equation appears to fit the empirical curves quite well for short wavelengths but fails completely for long wavelengths.

At about the same time Rayleigh [30] suggested an equation of the form

$$E = cT\lambda^{-4}$$

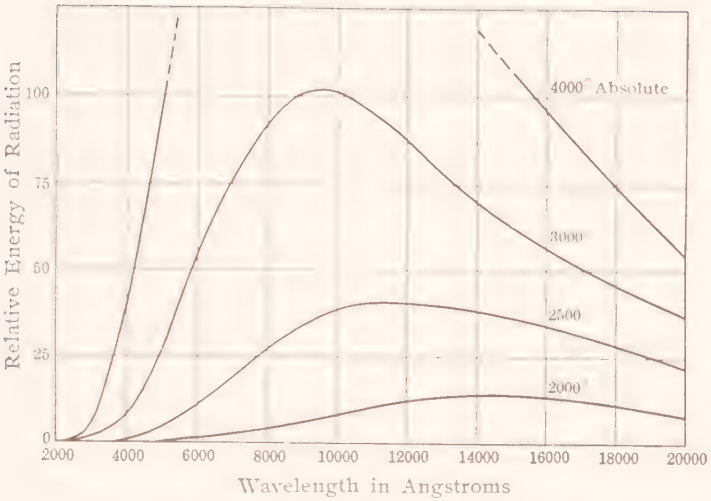

FIG. 7.—The spectral distribution of energy radiated by a black body at various temperatures.

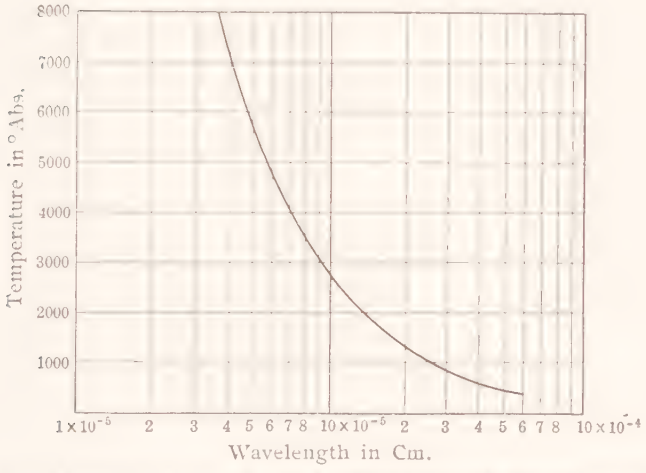

FIG. 7a.—A logarithmic curve showing how the wavelength of maximum energy shifts with the temperature of the source.

with c as a constant. This, contrariwise, agreed for long wavelengths and was quite wrong for short wavelengths.

Both of these equations were based upon the classical Newtonion laws of motion and upon the equally classical electromagnetic laws of Maxwell. Indeed, Rayleigh's formula ought to hold good for all wavelengths; but it does not.

Max Planck [31] came to the rescue with a revolutionary proposal that perhaps bodies do not after all radiate or absorb energy continuously, but rather discontinuously. By considering mathematically a simple linear oscillator as a typical example of a radiator he was led to suggest that its energy at any moment might be made up of a number of submultiple energies, each one of which is proportional to the frequency of vibration of the oscillator. Thus the unit of energy or *quantum* * of any perfect radiator he took to be $h\nu$, where h is a constant of proportionality, now known as *Planck's constant*. Beginning with this assumption and making use of the laws of probability he arrived at a definite expression for the energy distribution curves,

$$E = \frac{8\pi h\nu}{\lambda^4(e^{h\nu/RT}-1)} = \frac{8\pi hc}{\lambda^5(e^{hc/\lambda RT}-1)}$$

This formula fits the curves perfectly for all wavelengths and all temperatures. In it R is the constant of the general gas law evaluated for one molecule and is numerically 1.372×10^{-16}. The approved value of h itself is 6.55×10^{-27} erg. sec. The symbol c is the velocity of light, 3×10^{10} cm. sec. By letting ν be great enough

* The quantum is frequently called a *photon*.

so that $e^{h\nu/RT}$ is large compared to unity, the equation reduces to the common form of Wien's law:

$$E = \frac{8\pi h\nu}{\lambda^4 e^{h\nu/RT}}$$

which is quite valid for the range of visible radiations.

Ordinary radiation. All ordinary objects reflect light to a certain extent and usually differ in their absorptive powers for radiations of different frequencies.

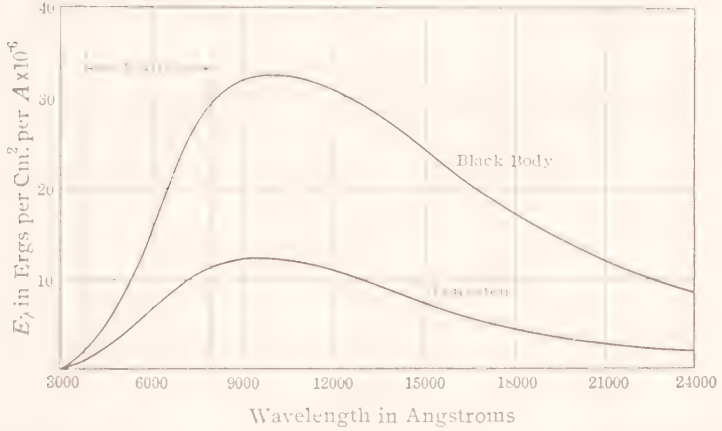

FIG. 8.—A comparison between the distribution of energy from an ideal black body and a real tungsten body, both at 2870° K.

Such objects cannot radiate as ideal black bodies, and hence their spectral energy distribution curves will not be as in Fig. 7, but will always have lower values of ordinate and a different value for the wavelength of maximum emission. In Fig. 8 the ideal curve for 2870° K is compared with the empirical curve for tungsten metal at the same temperature. The ratio of a given ordinate for the tungsten curve to the corresponding ordinate of the ideal curve is called the *spectral emissivity* of tungsten

for that frequency and that temperature. Figure 9 gives empirical curves for the spectral emissivity of tungsten.

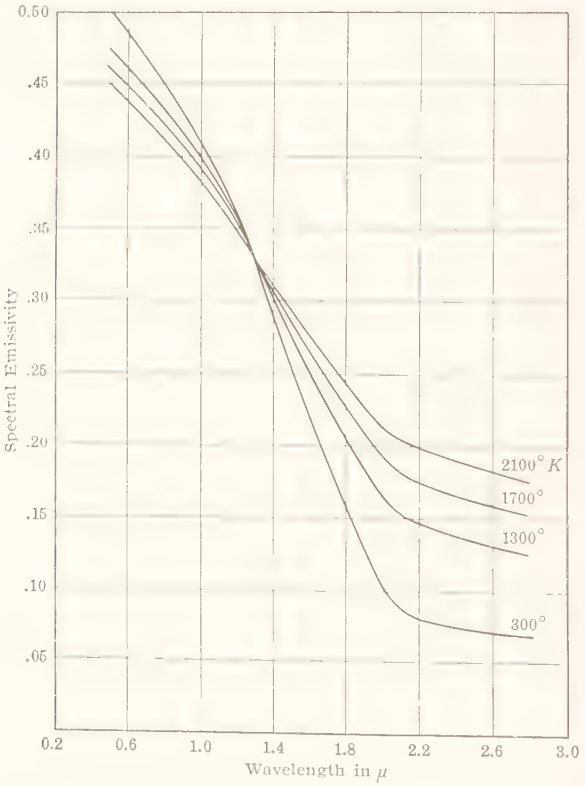

FIG. 9.—Variation of the spectral emissivity of tungsten with wavelength and with temperature. (After Forsythe and Worthing, by courtesy of the Astrophysical Journal.)

The actual distribution of energy in a tungsten incandescent lamp can be directly measured by forming a spectrum of the radiation and receiving on a blackened

thermopile successive narrow regions of the spectrum. The pile develops a voltage proportional to the incident energy. For ordinary incandescent temperatures, the maximum energy emitted lies in the near infra-red. The temperature of such filaments are usually determined by comparison with a standard lamp through calibrated color filters or by means of a calibrated device known as an optical pyrometer.

We have noted that the human eye is sensitive only to radiations comprising a single octave of frequencies. Just how deep a red and how high a violet one may perceive will vary somewhat with individuals, but for convenience we may state that the wavelengths of visible or luminous radiations lie between 4×10^{-5} cm. and 8×10^{-5} cm. Since the centimeter is a large unit with which to measure wavelengths of light, it has been customary to use the *Angstrom*, which is equivalent to one hundred-millionth of a centimeter. Thus the visible range lies between 4000 A and 8000 A. Still another unit preferred by many is the *millimicron*, which is one billionth of a meter or equals 10 Angstroms. A wavelength of 4000 A may be expressed also as 400 mμ. Naturally a *micron* is a thousand times larger.

Photometric measurements.—For two reasons the eye is not reliable as a judge of the intensity of light emitted by a source. First, its response is not proportional to the intensity. For a given intensity, the increment required for detection by the eye is proportional to the intensity itself. In other words, the brighter the source becomes, the less sensitive the eye becomes to any further increase. Secondly, the eye is not equally sensitive to all colors. The normal *visual sensitivity* curve is given in Fig. 10. The maximum occurs at

about 5550 A, the curve being almost symmetrical on both sides. If a yellow light and a red light of equal radiant energies were to be compared by the eye, the former would seem the brighter. Thus for the visible range it is important to distinguish between the actual radiation of energy from a source and the luminous radiation as visually determined.

In order to make comparisons of intensity, it is necessary to have a standard unit. Originally the unit was a *candle* made of spermaceti weighing $2\frac{7}{9}$ ounces and

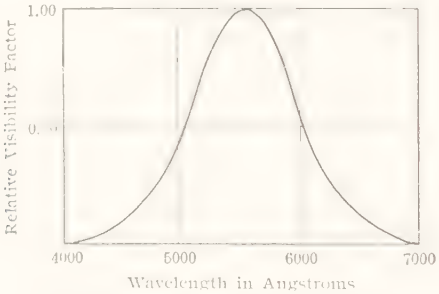

FIG. 10.—The visual sensitivity curve of the human eye.

burning at the rate of 120 grains per hour. Such a crude source was defined to have a *luminous intensity* of one *candlepower*. This has been superseded by the Vernon-Harcourt pentane lamp of ten candlepower or the German Hefner lamp of 0.9 candlepower which uses amyl acetate for fuel. Either of these primary standards is quite reliable and reproducible when built and operated according to definite specifications. For most purposes secondary and tertiary standards are employed consisting of tungsten filament electric lamps calibrated from primary sources by recognized experts. Actual comparison of the luminous intensities of two sources

can be made only when the sources are of the same color or are effectively reduced to the same color by means of a compensating filter.

For investigating the sensitivity of photocells to white light, it is customary to employ a tungsten lamp with concentrated filament. The temperature of the filament at normal voltage is measured in order to gain information with respect to the spectral distribution of energy, and then the corresponding candlepower is determined by comparison with a secondary standard. However, the amount of light from the lamp that passes into the cell through an aperture of definite area depends on the distance of the lamp. A new factor, *intensity of illumination*, must be considered. To make this clear, imagine a source of one candlepower irradiating a screen at a distance of 1 foot. The intensity of illumination on the screen is said to be one *foot-candle*, and the quantity of light that falls per second upon each square foot of the screen is called one *lumen*. If the candle were moved to a distance of 2 feet, the radiation, having now a radial reach twice as long would have to cover four times as much surface, and each square foot on the screen would receive only one-fourth as much light as before. In general, the intensity of illumination at a screen or aperture is inversely proportional to the square of the distance from the source of light, provided the source is small enough to be considered the center of the imaginary spherical surface on which the screen lies. More specifically, to determine the intensity of illumination in foot-candles at a surface, divide the candlepower of the source by the square of its distance in feet from the surface. To determine the light flux in lumens upon the surface, multiply the area of the screen

in square feet by the intensity of illumination in foot-candles.*

There can be no definite conversion factor for changing units of radiant energy into units of luminous intensity because the value of the latter depends on color distribution. For example, two sources of the same candlepower may be radiating entirely different quantities of total energy. Hence the luminous intensity and total radiant energy must be measured independently. The part of the radiant energy which lies in the visible region may be separately determined, but how intense it will appear to the eye depends on the distribution of the visible energy with respect to color. If we confine ourselves to just one color, say 5550 A, to which the eye is most sensitive, it is possible to compute a factor which has been termed the *least mechanical equivalent of light.* The candlepower of a given source and its spectral energy distribution curve are first determined. Then by comparison of the ordinates of the distribution curve with corresponding ordinates of the color-sensitivity curve of the eye, the ratio of energy to intensity may be found for the desired color. In this manner Ives [32] arrived at the value 0.0016 watt as equivalent to one lumen for 5550 A.

Drude in his *Theory of Optics,* has presented some interesting data on the amount of energy emitted in the whole visible range by a Hefner lamp. Assuming Turnlirz's value of 0.1483 gram-calories per second as the total emission per unit solid angle from the lamp, Drude computes that the luminous energy per unit solid angle is 1.51×10^5 ergs per second. Correspondingly,

* An equivalent method is to multiply the candlepower of the source by the solid angle subtended at the source by the area of the screen or aperture.

the energy equivalent to 1 candle-meter is 15 ergs per second. The eye situated at a distance of 1 meter from a standard candle receives luminous energy at the rate of about 1 erg per second. This flux of energy is so small that it would require 1 year and 89 days to heat 1 g. of water 1° C. If we assume that the eye can just barely detect a star of the sixth magnitude, the limit of visibility would correspond to an incidence of about 10^{-8} ergs per second.

II. PHOTO-EMISSIVE EFFECT

Up to this point we have employed the term "photo-electric effect" as descriptive of the process of releasing electrons under the action of radiation. Strictly speaking, the term also includes any electrical phenomenon which is caused by radiation. For our purpose, such phenomena may be grouped into three classes: (1) change in ohmic resistance of matter; (2) chemical or physical reaction to produce an electromotive force; and (3) actual liberation of electrons. The first class, illustrated by the behavior of selenium, will be referred to as the *photo-conductive effect*. The second, illustrated by the copper oxide electrolytic cell, we shall call the *photo-voltaic effect*. The third, in which we are particularly interested, may be described as the *photo-emissive effect*. The first two effects will be treated in a subsequent chapter; the theory of the photo-emissive effect will be considered at once.

Einstein's equation.—Just as the classical physics was inadequate for explaining the distribution of energy of a black body, it likewise failed to account satisfactorily for the release of electrons by radiation. It has

been computed that if a surface is faintly illuminated at the rate of 0.56 erg per sq. cm. per second, and it is assumed that the illumination is continuously distributed, it would require 200,000 hours for one electron to receive sufficient energy for it to be ejected from the surface; and yet actual measurements revealed that electrons were emitted at least as soon as one ten-millionth of a second.[33] In 1905 Albert Einstein [34] proposed that photo-emissive phenomena could be accounted for by adopting Planck's quantum theory of radiation and assuming that when a quantum of energy $h\nu$ reacted with an electron, the latter would acquire the total quantum and be released in possession of an equivalent amount of kinetic energy. Einstein's equation for the photo-electron is:

$$\tfrac{1}{2}mv^2 = h\nu - P,$$

where P represents the energy lost by the electron in freeing itself from the influence of surrounding atoms while leaving the parent body. We notice at once that if $P = h\nu$, the velocity of emission of the electron is zero, and hence there must be a certain minimum frequency, say ν_0, below which no frequency is able to liberate an electron. We can set $h\nu_0 = P$ and write

$$\tfrac{1}{2}mv^2 = h(\nu - \nu_0).$$

This minimum value is known as the *threshold frequency*. Its reality is proved by experiment.

The equation also states mathematically that the energy of emission is directly proportional to the frequency, which is the second empirical law previously noted. The quantum idea in itself would agree with the first empirical law that the number of electrons

released is proportional to the intensity of the light, for the greater the intensity, the more quanta to function.

The term P in Einstein's equation, being a measure of the work done by the electron during egress, is called the *work function* of the given surface. It is, of course, different for different electrons, but there is always a least value not zero for a given surface. For pure metals the least work function is rather definite. Table 2

TABLE 2

LEAST WORK FUNCTIONS FOR SEVERAL ELEMENTS
(Selected)

	Volts		Volts
Lithium	2.36	Cesium	1.36
Sodium	1.82	Calcium	2.4
Potassium	1.55	Strontium	2.0
[illegible]	1.45	Barium	1.7

records empirical values for a number of elements. The figures are given in volts because they are usually determined by illuminating a surface with monochromatic light and measuring the smallest reverse voltage required to prevent electrons of maximum energy from reaching a second electrode. Since the energy acquired by an electron of charge e in falling through a voltage V is Ve, if the reverse or retarding potential just overcomes the kinetic energy of an electron, we have

$$Ve = \tfrac{1}{2}mv^2 = h\nu - P_0,$$

or $P_0 = Ve - h\nu$. Because V is always small, it is quite essential that correction be made for any independent potential difference between the electrodes, chiefly con-

tact difference of potential, which exists for all dissimilar substances taken in pairs, and which may either oppose or aid the release of the electrons.

One definite aim in the development of sensitive photocells is to reduce the least work function to as low a value as possible.

Einstein's equation has received experimental attention by many investigators but most notably by R. A.

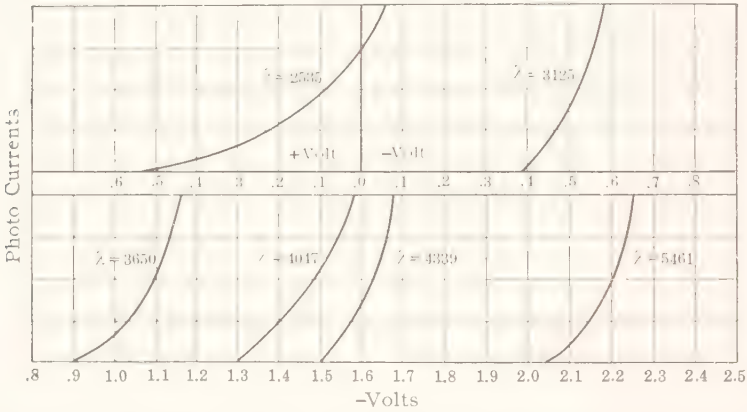

FIG. 11.—Retarding potential curves for electrons released from sodium by various frequencies of radiation. (After Millikan, by courtesy of the Physical Review.)

Millikan.[35] He made very accurate measurements of retarding potentials and contact potentials for a surface of sodium in an evacuated vessel. The sodium surface was kept bright by means of a paring tool enclosed in the same vessel and operated electromagnetically. Figure 11 is a reproduction of the curves obtained. Each curve represents the electronic current from the sodium to a collecting cylinder decreasing as the opposing field more and more effectively checks the velocities of emission of the electrons. The extrapolated intercept on the

axis of abscissas indicates the voltage for which even the fastest electrons are forced back into the sodium. In Fig. 12 these intercepts are plotted against corresponding frequencies of the monochromatic light used for each curve. The result is an exactly straight line. Its slope $dV/d\nu$ can be evaluated from the equation $Ve = h\nu - P_0$ and is equal to h/e. Using his own accurate figure for e, 4.774×10^{-10} electrostatic units, he computed for h the value 6.57×10^{-27} erg-sec., which he judges to be correct to ½ per cent. The result

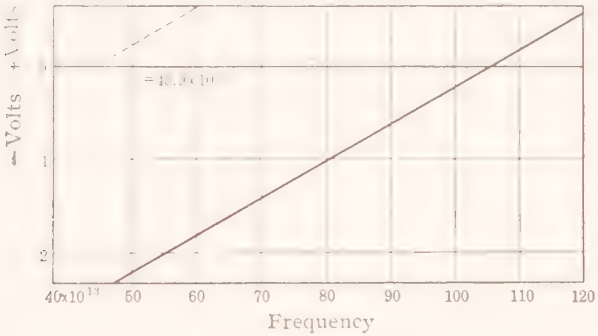

FIG. 12.—The voltage intercepts of Fig. 11 plotted against the corresponding frequency of each radiation. The slope of the curve is h/e. (After Millikan, by courtesy of the Physical Review.)

is definitely a precise check on Einstein's equation and upon the quantum theory.

Structure of matter. We have already observed that the pioneering investigations of J. J. Thomson revealed the existence of the negatively charged electron as a constituent unit of all matter. There is only one other structural unit, and that is a positively charged nucleus called the *proton*. Its mass is 1.67×10^{-24} grams or 1845 times that of the electron, but its charge, though opposite in sign, is exactly equal in value. All atoms of

matter, whether simple or complex, are made up only of protons and electrons in equal numbers. The most successful mechanical scheme conceived for the structure of atoms was that first propounded by Ernest Rutherford [6] in 1911 and modified by Niels Bohr [7] in 1913 to accord with the quantum theory. The Rutherford Bohr model of the *hydrogen atom* comprises one proton as a massive nucleus and one electron revolving about it in a circular orbit in much the same manner as the moon revolves about the earth with electrostatic attraction playing the role of gravitation. The next simplest atom, *helium*, has a composite nucleus, consisting of four protons and two electrons in a compact orbital system, with two other electrons describing outer circular paths about the doubly charged core. Atom number three is *lithium*, the lightest of the alkali metals. Its nucleus may be made up in either one of two ways: 6 protons and 3 electrons or 7 protons and 4 electrons. For both types, two external circular orbits are occupied by electrons and a third electron describes a larger elliptical path with the nucleus at one focus. These two kinds of lithium, which act precisely the same chemically, are said to be isotopic. Some elements have a great number of *isotopes*.

The important point to observe in lithium is that the single outside electron during part of its orbit is separated from the resultant triple charge of the nucleus by the neutralizing effect of the two circular orbits so that it would not require a great amount of energy to release it entirely from the atom.

As the elements are considered in order of their relative weights, the nuclei become more and more complex and the external electrons more and more numerous.

The largest part of the mass of an atom is due to the protons which are always localized in the nucleus. The number of protons in the nucleus is a direct measure of the weight of the atom as compared to hydrogen. A lesser number of electrons in the nucleus completes a stable system and the number of protons in excess of the electrons determines the resultant positive charge, which in turn determines the number of electrons that must exist in external orbits to constitute a neutral system altogether. Each succeeding atom in the compiled list of known elements has just one more external electron than the previous atom. In general, each time that a group of external orbits completes a self-sufficient symmetrical system the resulting atom is inactive chemically, being one of the inert gases like *helium, neon* or *argon.* Then the very next atom in order of structure has the added external electron in a new enlarged orbit as was described for lithium. Such atoms make up the alkali family. As we pass through this cyclic arrangement of the elements, we note *sodium* with 10 outer electrons in completed systems plus one lone electron describing an elongated ellipse: *potassium* with 18 plus 1; *rubidium* with 36 plus 1; and ultimately *cæsium* with 54 plus 1. There should also be an element number 87 with 86 outer electrons plus 1, but it has never been discovered.

We should expect that as the intervening negative orbits between the lone planetary electron and the charged core become more and more numerous, the attraction for the single electron when at its outermost point would become smaller and smaller. Hence the quantum of energy required to liberate an electron should decrease as the atomic number of the alkali atom increases. We shall find this to be true.

It is also worthy of note that the alkaline earths — *beryllium, magnesium, calcium, strontium,* and *barium*— differ externally from the alkalis only by the presence of two remote electrons instead of one. Of course, there is an effective double positive charge acting upon them. Barium and strontium have been employed successfully in photocells.

When radiant energies of such high frequencies as comprises X-rays are incident upon atoms, the quanta are sufficiently great to eject electrons from the intermediate systems of orbits. And γ-rays, which are emitted by radioactive materials, can even tear electrons from the nucleus itself.

Color sensitivity. Early work already described indicated definitely that some photo-emissive surfaces are sensitive to longer wavelengths than others. For example, the alkali metals are caused to emit electrons by visible radiations, whereas a surface of copper oxide is not at all responsive except to ultra-violet. Pohl and Pringsheim [28] showed for a liquid alloy of sodium and potassium that the number of electrons released by unit energy of incident radiation increased from zero in the red end of the spectrum to a maximum in the near ultra-violet and then decreased to a low value again, only to start rising for still higher frequencies. Compare Fig. 13. The peak of the curve is probably due to some inherent natural period in the active material. The underlying consistent rise in activity for higher frequencies would logically follow from the fact that the corresponding quanta become large in comparison with the work function. The relative response of a photocell for various frequencies of radiations is termed its *color sensitivity.* More recently a set of careful meas-

urements have been made by Miss E. Seiler [7] on the color sensitivities of cells containing severally all of the alkali metals. In Fig. 14 are shown the curves illustrating her results. Two points of importance may be observed: first, the wavelength of maximum sensitivity increases in the same order as the atomic numbers of the alkali elements; secondly, the relative magnitude of the number of electrons released at the maximum decreases from lithium to cesium.

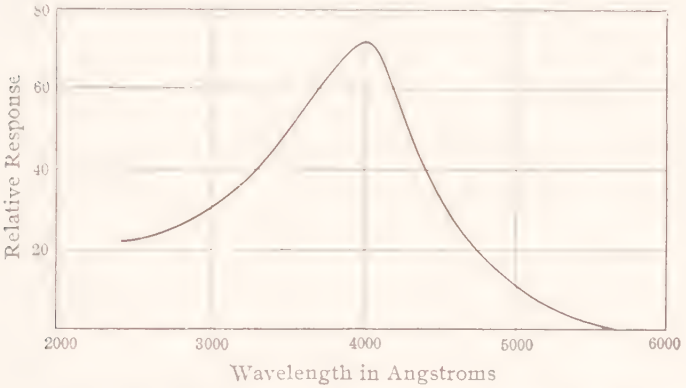

FIG. 13.—Color-sensitivity curve for a liquid alloy of sodium and potassium.

Recalling that an ordinary incandescent lamp radiates maximum energy in the near infra-red, it can readily be perceived that it is highly desirable to discover a photo-emissive material which will have its sensitivity peak in the near infra-red and besides have the sensitivity quantitatively high. A later chapter contains empirical curves for modern cells which aim to fulfill these requirements.

Photosensitive films.—Since the work function of a material is essentially dependent upon electrostatic forces active at and near the surface, it is only to be

expected that the thickness of the layer of material employed in a cell must have a distinct influence on the number of electrons freed by a given source of white light. Experimental results have shown that as a rule highest responses are obtained from cells containing layers so thin as to be invisible. We may cite as quanti-

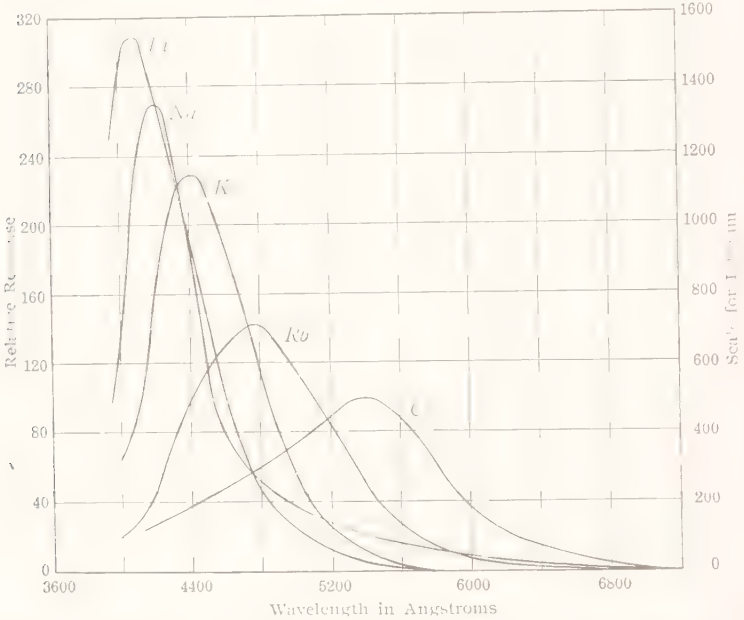

FIG. 14.—Color-sensitivity curves for the alkali metals. (After Miss Seiler, by courtesy of the Astrophysical Journal.)

tative evidence the work of H. E. Ives [40] with thin films of rubidium on glass. Taking advantage of the optical property of this alkali to rotate the plane of a polarized beam of light by an amount proportional to the thickness of material traversed, he was able to prove that the most sensitive films obtained were of the order of one atom thick.

J. Becker [41] has had some success in empirically confirming a theory of the adsorption of positive ions, which he terms "*adions*", by the base substance upon which the active element is deposited. Referring specifically to barium on tungsten, he argues that under equilibrium conditions of temperature of the tungsten and pressure of the barium vapor, positive ions of the barium attach themselves to the tungsten in such a fashion that the remaining valence electron describes an orbit down into the surface and leaves an unneutralized positive charge outward. Any electron liberated at or near the tungsten surface would be aided in its egress by this positive layer. Now if the layer should be several atoms thick, the outermost ones would not be appreciably polarized either by their similar neighbors or by the too remote base substance; hence, an electron once released by radiation from any atom could not pass through the external surface except by its own excess energy.

Thus the most recent successes in photocells have resulted from the deposition of alkali in thin films upon metals or compounds so chosen as to decrease materially the work function.

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CHAPTER III

MECHANICAL FEATURES

With respect to physical structure all practical types of photocells may be divided into two classes: *central anode* and *central cathode*.

Central anode type. Most commercial cells have the positive electrode either in the general form of a ring or a grid or a rod situated near the geometric center or axis of the cell. The negative electrode, which comprises the sensitive cathode, more or less completely surrounds the anode and may assume the form of a coating on the inner wall of the cell or may be a flat or semicylindrical plate sensitized in a definite manner. Of course, the wall of the cell must have at least a small translucent area through which light may reach the cathode.

The cathode area in this type can be made almost as large as the total surface of the bulb and hence is capable of emitting a relatively large number of electrons for a given sensitivity. This is counterbalanced somewhat by the smaller area of the anode which requires a relatively high voltage to collect all the electrons. If the cathode forms a coating over the entire wall except for a minute window, conditions for black-body absorption of light are approached and the efficiency of the cell is somewhat increased.

Central cathode type.—Cells may be made with a central sensitive surface surrounded by a larger anode

surface. Such a structure is common in radio tubes where the emitter is the thermionic filament. Since usually the chief aim in application of photocells is to receive as much light as possible upon the cathode, the small surface is not desirable. In laboratory investigations, where, for example, it is wished to study the behavior of electrons liberated in a powerful radial field, this type of cell proves very useful. A notable feature also is the fact that an applied voltage of less than one volt is sufficient to collect most of the electrons that can be released from the cathode.

Shapes and sizes of cells. It has been found that any unusual attempts to secure multiple reflections of light upon the cathode have not secured results in proportion. In general, the first incidence of the light determines the magnitude of the ultimate current. Hence it is more important to have the cell shaped so as to expose as much sensitive surface as possible to a given intensity of illumination. Imagine a spherical cell 2 inches in diameter with the cathode on the inner wall and provided with a 1-inch circular window. If the illumination at the window is, say, 50 foot-candles, a certain number of electrons will be released. Now if the cathode coating were transformed into a central disk 1 inch in diameter, and had the same intrinsic sensitivity, the number of electrons released would be almost the same. But if the disk were increased to 2 inches in diameter, for the same intensity of illumination the total response would be four times as great.

Thus a shape of cell is desirable which will permit the largest direct exposure of active cathode. Since in practice spherical bulbs or blanks are provided with small necks, it is becoming customary to use cylindrical

tubes with necks almost as large as the tube proper. In these a large metal plate may be mounted and sensitized. Incidentally, the discussion indicates that the ideal conditions would be obtained by depositing a translucent cathode on the inner wall of either a spherical bulb or cylindrical tube.

Theoretically, the larger the volume of the photocell, the more light can be collected to release electrons, so that the large cell might seem to be the ultimate one. As a matter of fact the tendency has been in the field of television to use larger and larger cells as the demand arose for more and more efficient light collection. Such large cells are difficult and expensive to manufacture, and are unwieldy to manipulate. Hence, the rather sensible idea of employing large reflectors with small replaceable phototubes in their focal space has come into application. For certain uses it is also feasible to use a large condensing lens with small cells. Naturally the intensity of the focused light dare not be so great as to deteriorate the sensitive surface either by excessive heat or by photo-chemical decomposition.

For all applications where rapidly fluctuating light impulses are received, especially in television, it is important to minimize the electrostatic capacity between electrodes. In large cells, the anode may be made relatively small and the spacing large. In small cells, the reduced size of the cathode tends to counteract the effect of closer electrode spacing so that the capacities of large and small cells can be of the same order of magnitude.

Electric leakage. How serious electric leakage between electrodes may be depends on the relative magnitude of the electronic current provoked by the radia-

tion employed. In the early cells, even with strong illumination, sensitive galvanometers were required to measure the response; and hence very small leakage currents were serious enough to mask photoelectric measurements. With very sensitive cells, precaution against leakage is essential only when feeble illumination is used. An effective method for shunting this small leakage out of the galvanometer circuit is to introduce somewhere in the high resistance path a conducting ring which is connected to ground. It is a simple expedient also to use as long a path as possible by having the terminals at opposite ends of the cell or by enclosing either or both wires at the seals by long enveloping insulating sleeves.

The rate at which an alkali metal will distribute itself over insulating parts of a photocell depends mainly on its vapor pressure in the cell. In general, the vapor pressures of free alkalis increase with atomic weight in somewhat the same manner as the melting points decrease. (See Table 3.) The melting points of pure

TABLE 3

PROPERTIES OF ALKALI METALS

(Hopkins, Chemistry of the Rarer Elements)
D. C. Heath & Co., Publishers

	Lithium	Sodium	Potassium	Rubidium	Cesium
Atomic weight	6.94	23.0	39.1	85.45	132.81
Specific gravity	0.534	0.9712	0.8621	1.532	1.87
Atomic volume	13.1	23.7	45.4	55.8	71.0
Melting point	186.0°	97.0°	62.5°	38.5°	26.5°
Boiling point	1400.0°	877.5°	700.0°	696.0°	670.0°
Specific heat	0.941	0.293	0.166	0.0792	0.0482
Color of flame	Crimson	Yellow	Violet	Violet	Blue

lithium and sodium are high enough that their vapor pressures are almost negligible at ordinary temperatures, and no appreciable distillation and subsequent condensation take place even over indefinitely long periods of time. But if a cell contains an excess of an alkali as volatile as cesium or even potassium, it is almost impossible to prevent ultimate distillation of a conducting layer between terminals. One practical precaution is to enclose the anode support wire in a glass sleeve provided at the free end with a metal cap which covers and encircles but does not touch. A practical remedy, in case the leakage exists, is to apply local heating permanently to evaporate the condensed alkali.

Recent methods of manufacture make it possible to use even cesium in tubes with both leads in a single press and still have an ohmic resistance between terminals of many thousands of megohms. This is done by using an extremely small amount of free alkali metal which is bound to the cathode surface during the process of formation.

Choice of glass.—For nearly all present applications of photocells only visible radiations are involved. Hence ordinary glass is used for the containing walls. Because of ease in working it is customary to use soft glass, but since common *lead glass* is rather readily attacked by alkalis, it is necessary—at least when baking schedules are followed—to substitute what is known as *lime glass*, which is only slightly susceptible to corrosive action. When lead glass is heated gradually in the presence of cesium, the latter attacks the lead oxide in the glass and unites to form a brown compound. This property, wholly objectionable from the point of view of transparency of the walls, becomes a valuable asset when

restricted to a definite section of the tube, insofar as the reaction provides a means of eliminating excess cesium.

For photometry of the ultra-violet it becomes necessary to use either *quartz* or else a special glass which is capable of transmitting short wavelengths.

CHAPTER IV

GENERAL METHODS OF PREPARING PHOTOCELLS

Photocells which respond to visible radiations all have for their sensitive material one of the alkali metals, lithium, sodium, potassium, rubidium, cesium, or one of the alkaline earths, calcium, strontium, barium, or some physical or chemical compound of an alkali or alkaline earth. The metals most frequently employed are sodium, potassium, cesium and barium.

It is convenient to classify cells by the general manner in which the sensitive element is introduced. The methods of deposition generally employed may be grouped under four headings: from *solution*, by *distillation*, by *electrolysis*, by *disintegration*.

Deposition from solution. The method of solution is not now in common use. The alkali metal is dissolved in a volatile solvent and the solution is applied to the portion of the bulb to be sensitized. Upon evacuation of the bulb, the solvent evaporates, leaving a rather uniform film of metal on the wall. This was the only method by which Kunz was able to manipulate lithium. As a solvent he used *aethylamine*. It was a cell of this type that Miss Seiler employed for measurements on the color sensitivity of lithium, the curve for which is given in Fig. 14.

Deposition by distillation.— Distillation of the alkali metals, sodium to cesium, may be carried out either

from an external supply through a connecting glass system to the cell or by direct evaporation from a pure supply introduced bodily into the cell before evacuation. Because of its relatively high melting point, 186° C., lithium cannot be distilled through glass systems, but it can be evaporated from a solid portion properly prepared and mounted within the cell. Dr. Ives [42] has suggested a practical method for preparing the lithium. A small hollow cylinder of steel is driven through a chunk of solid alkali, thus securing a protected core with only the exposed ends oxidized. The cylinder with

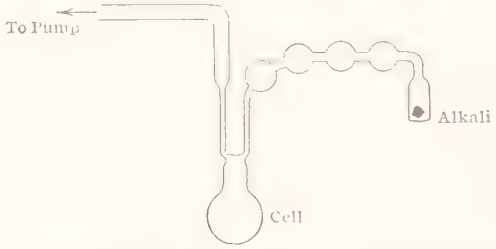

FIG. 15.—A series of distillation chambers for purifying an alkali metal and for introducing it into the cell.

its core is mounted in a bulb and is fitted with a fairly heavy plunger which bears down with its weight upon the lithium. When the cylinder is heated up by a high-frequency electromagnetic field, the molten lithium, ordinarily unable to seep through its oxide crust, is forced to do so by the plunger and at once evaporates to condense on the walls of the bulb.

The other alkalis may be rather inconveniently distilled from an original supply in a rather remote part of a glass appendage through a series of condensing chambers, as shown in Fig. 15, becoming purer at each stage, until ultimately the vapor is driven into the cell, after

which the whole appendage with its chambers is sealed off. Within the cell proper, the alkali may be permitted to condense directly upon the glass walls or else upon a conducting metallic coating, such as silver, previously deposited. The successive distillations may be effected by the simple expedient of applying a Bunsen flame.

One novel method for introducing alkali metals into cells takes advantage of the reduced activity of these elements at low temperatures. For example, a lump of potassium is melted at low pressure in a glass bulb, and the molten alkali is then decanted into a side tube and sealed off. When cool, the tube is immersed in liquid air. Any portion of the tube with its potassium core may then be snapped off and quickly inserted into a distillation appendage leading to the cell. The appendage may be sealed off and the entire manifold evacuated before the alkali becomes warm enough to oxidize.

Hydration of alkalis. All alkali cells prepared either by the method of solution or of distillation may be increased in sensitivity by a hydrogen discharge with the one exception of cesium. For example, potassium may be made a hundred times as sensitive as in its natural state. With a pressure of 2 or 3 mm. of hydrogen, an applied voltage of about 300 volts between anode and alkaline cathode will cause a glow discharge to pass through the gas. The potassium at once becomes brilliantly colored, in its final state becoming a sort of peacock blue. The process requires only a few seconds. Both the coloration and the corresponding increased sensitivity will gradually disappear unless an inert gas such as argon is introduced after the excess hydrogen is pumped out. With the inert gas present, the cell may remain sensitive for many months. Per-

haps more cells of this type have been made in the past than of any other kind.

Deposition by electrolysis. At least sodium and potassium may be deposited within a cell by electrolysis through the glass walls themselves. R. C. Burt [43] has developed and described a process by which the purest of sodium can be introduced into an evacuated bulb by this method. He credits E. Warburg with the discovery of the electrolytic passage of sodium into Geissler tubes

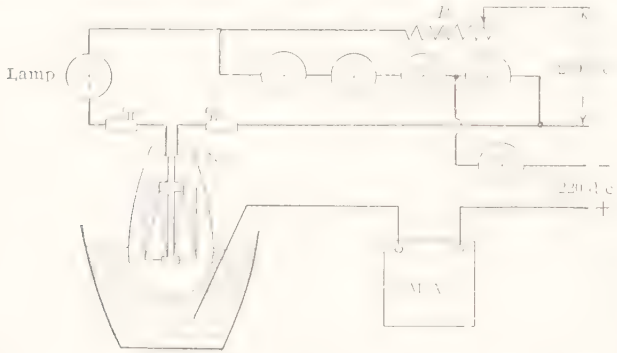

FIG. 16.—A convenient circuit to use for the electrolysis of sodium through glass. (After Burt, by courtesy of J. O. S. A. and R. S. I.)

in 1884 by using voltages higher than 1000 volts and employing ionization currents within the tube to complete the circuit. A. W. Hull suggested the use of the electronic current from a hot filament for completing the electrolytic circuit in the case of high-vacuum tubes.

Figure 16 is a diagram of the circuit devised by Burt in 1925. The bulb into which the sodium is to be introduced, say a 60-watt lamp, must be made of soda glass. It is placed in a bath of molten *sodium nitrate* ($NaNO_3$, melting point 312° C.) which also contains a heavy copper wire as anode. When the filament is incandescent,

electrons travel to the glass and neutralize the sodium ions produced at the surface by the direct-current field, the ions becoming neutral atoms which evaporate to condense in the cooler parts of the bulb. The group of four lamps in series are designed to connect the negative direct-current terminal effectively with the mid-tap of the filament. This causes the electrolytic current to be distributed more uniformly over the area of the filament, and it is not overheated. The other lamps shown are merely to limit and stabilize the electrolytic current. Photoelectric cells prepared by this process are quite permanent. Dr. Burt states that after exposing one of these cells all day to full sunlight, he was able with the same cell to measure accurately small variations in very weak illuminations. Unfortunately the sensitivity is not high compared with that of more recent cells.

Burt's efforts to send potassium through glass failed because when the sodium atoms were displaced by the dissimilar potassium atoms, molecular strains were introduced which resulted in fracture. The following year V. Zworykin[44] succeeded in accomplishing the desired result by utilizing a pure potash glass containing no soda. With bulbs of this material and a bath of molten *potassium nitrate* (KNO_3) photocells of equal quality with the sodium cells were made.

Deposition by decomposition.—Disintegration of compounds may be very simply accomplished by *thermal* treatment. This scheme has been successfully employed in the Zworykin *cesium-magnesium cell.*[45] The mechanical structure can be clearly understood from Fig. 17. The press contains two wires one of which is sealed to the inner wall of the bulb, the other being centrally located and provided with a ring of metallic rib-

bon. A glass sleeve topped but not touched by a metal cap, surrounds the central wire and insures effective insulation. Upon the ring are welded a few bits of magnesium and also there is painted a small quantity of an aqueous solution of *cesium trinitride* (CsN_3). After the cell is exhausted and baked out in the usual manner, it is at once sealed off from the manifold. When the ring is heated by a high-frequency field, the magnesium evaporates and condenses on the walls of the bulb, and at the same time the trinitride is thermally decomposed. The free nitrogen is chemically bound by the active magnesium during its flight through space, and ultimately the hot cesium vapor condenses in an invisibly thin film upon the silvery magnesium coating. A window is made in an appropriate position by applying a Bunsen flame externally, and the cell is done. The actual appearance of the cell is shown in Fig. 18.

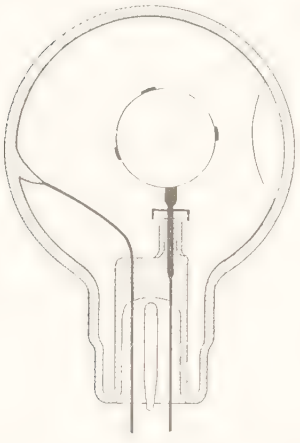

FIG. 17.—A cross-section of the structure of a cesium-magnesium photocell.

The sensitivity of the vacuum cesium-magnesium cell is of the order of 2 microamperes per lumen, roughly ten times that of the hydrogenated potassium cell without gas amplification. A typical color-sensitivity curve is shown in Fig. 19.

T. W. Case [6] makes use of thermal decomposition in his *barium-silver cell*. A barium compound is applied to a central ring which is later heated by a filament current until barium and probably barium sub-oxide are

released and evaporate over onto a silver coating which has been previously deposited. The surface is further sensitized by *ionic bombardment*. Figure 20 gives the color sensitivity curve for the Case barium cell and also for his strontium cell, which is somewhat more reliable in action though less sensitive to the red.

FIG. 18.—The actual appearance of one type of cesium-magnesium photocell.

By far the most sensitive cell ever produced, insofar as is revealed in literature,[47] is the *cesium-oxide-silver cell* originally developed by L. R. Koller [48] and H. E. Thomson of the General Electric Company and later improved in conjunction with the research laboratories of the Westinghouse Electric & Manufacturing Company. In one form of this cell, cesium, released by thermal decomposition of a pellet consisting of, say, *cesium chloride* and *calcium*, condenses on a silvered cathode plate which has been oxidized. Baking in a furnace causes a reaction between the alkali and the oxygen which ultimately results in the formation of oxides of cesium with doubtless a monatomic layer of cesium over all.[18] Figure 21 shows the appearance of a cell of this type.

The vacuum sensitivity of this cell to light from a Mazda lamp is of the order of 25 microamperes per lumen. The color sensitivity curve shown in Fig. 22 is notable for its double maximum, one at about 3200 A and the other at about 7800 A. It is the peak in the deep red which causes its response to be so great for ordinary light.

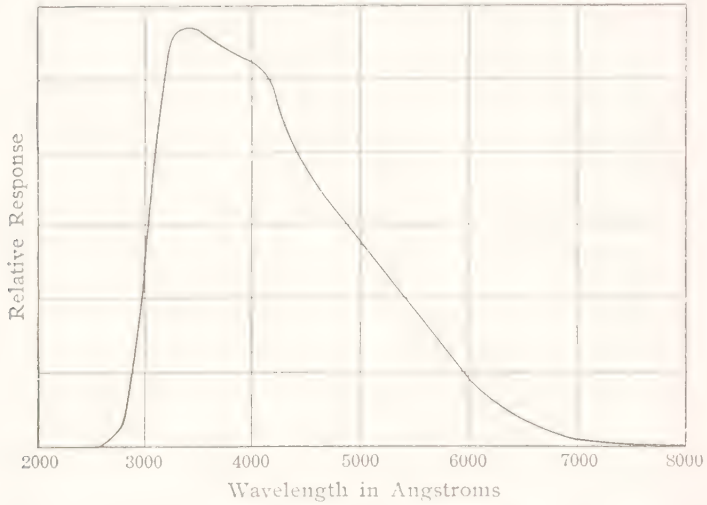

FIG. 19.—The color-sensitivity curve of a cesium-magnesium photocell.

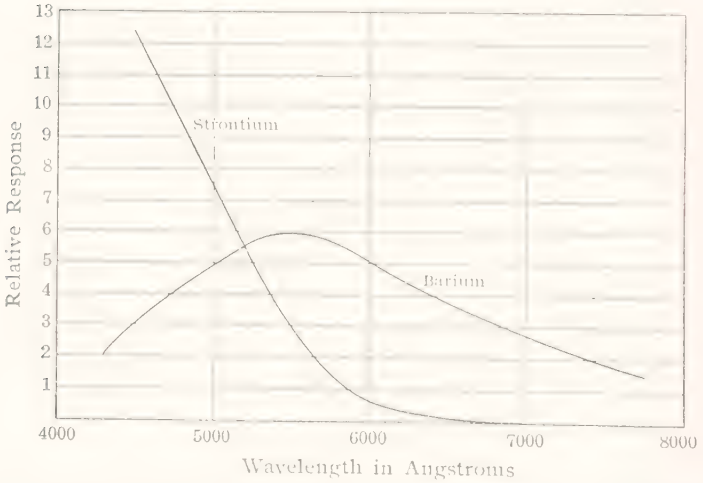

FIG. 20.—Color-sensitivity curves of barium and strontium photocells made by Case.

We mention in a class by itself the latest type of cell developed in the Bell Telephone Laboratories by H. E. Ives and O. R. Olpin.[49] This cell, intermediate in sensitivity between the cesium-magnesium and the cesium-oxide-silver types, has for alkali either sodium or potassium. Greater sensitivity is attained by the introduction of slight traces of *sulphur* and *oxygen*. Also organic dyes like *alizamine blue* are employed for staining the surface in analogy with the sensitization of photographic emulsion to longer wavelengths. The composite treatment has the effect of creating a red-sensitivity, more noticeable with sodium than with potassium.

FIG. 21.—One type of cesium-oxide photocell.

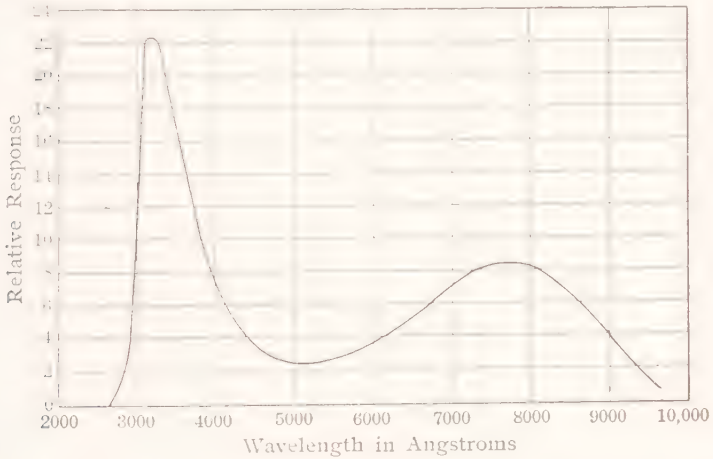

FIG. 22.—Characteristic curve for one type of cesium-oxide photocell.

Cells for ultra-violet.—Photoelectric cells which are sensitive chiefly to the ultra-violet are unique in the sense that plain metal cathodes suffice. A metal is chosen which will respond best in the region of frequencies whose intensities are to be measured. The first suggestion for practical application of the photoelectric effect was for photometry of the ultra-violet; and now since so much interest is attached to the therapeutic value of ultra-violet radiation and to the art of photochemistry, attention has again reverted to the development of practical cells for measuring the intensity of healthful rays from therapeutic lamps and of photochemical radiations.

One of the more recent practical cells for measurement of ultra-violet radiations has been developed by H. D. Griffith.[50] A cathode, consisting of specially prepared *cadmium*, is sealed in an evacuated vessel of glass. A window of plane-parallel quartz plate serves to admit short wavelengths to the cathode. The spectral region of sensitivity for the cadmium cell lies between the limits 2000 A and 3000 A.

It has been fairly well established by the medical profession that anti-rachitic radiations comprise the short range between about 2800 A and 3200 A. Hence the cadmium cell does not seem to be well adapted to measure the intensity of these rays.

Because of the unusual sensitivity of *lithium* in the violet (note the separate scale of the sensitivity curve for lithium in Fig. 14*c*, this alkali has been suggested as a likely substance.[51] However, a much superior element for the purpose has been recently employed by H. C. Rentschler[52] of Westinghouse Lamp Co. He makes use of metallic *uranium* as a cathode and encloses

it in a special glass transparent to radiations as short as 2800 A in wavelength. An erythema curve has been published by Hauser and Vahle [44] and is shown in Fig. 23. The uranium cell in Corex glass responds throughout the same region. A circuit employing the uranium cell is described in Chapter XIII.

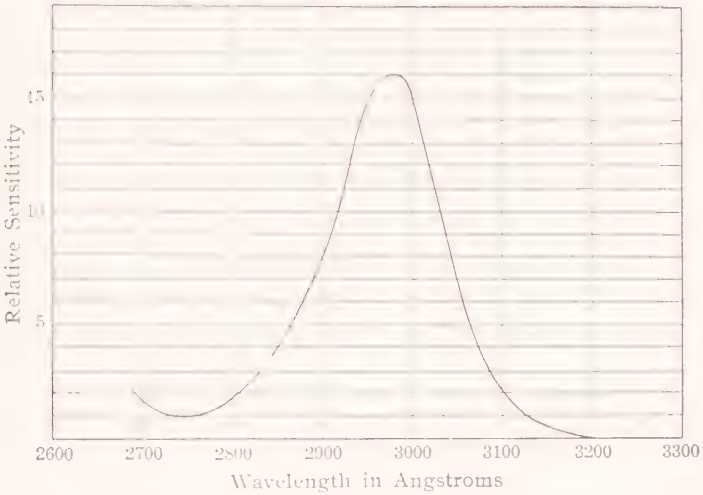

FIG. 23.—A curve representing the relative speed with which the human skin is reddened by various wavelengths in solar radiation.

For the region below about 3700 A, Rentschler suggests the use of *thorium*; and for the region blue to ultra-violet, the metal *cerium*.

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CHAPTER V

THE VACUUM PHOTOCELL

Of the two types of cells, high-vacuum and gas-filled, the first is naturally more simple in its general functioning.

Propagation of photo-electrons in vacuum. Ives and his assistants [1] have shown rather definitely by direct measurements that photo-electrons, under all conditions of illumination, are released symmetrically about the normal to the emitting surface as plotted in Fig. 24. This is true regardless of the angle of incidence of the light or of the direction of vibration of the electric vector. The actual *distribution in numbers* of electrons in a given plane containing the normal to the surface was found to follow closely *Lambert's Cosine Law* for the scattering of light by matt surfaces. This law may be stated in the following manner: if light of unit intensity is incident at an angle i upon a non-specular surface, the amount reflected per unit area at an angle e upon unit area at a distance r is

$$I = \frac{k \cos i \cos e}{r^2}$$

where k is a constant depending on the nature of the diffusing surface and the color of the light. Thus if light is incident at a given angle upon a small emissive spot, the numbers of electrons emerging in various

directions will be approximately in accordance with the polar diagram of Fig. 24. At all points in the interelectrode space, except at the surface of the cathode, the Lambert distribution is of course valid only when the effective electrostatic field at the cathode is zero. For fields of increasing strength, the electrons tend more

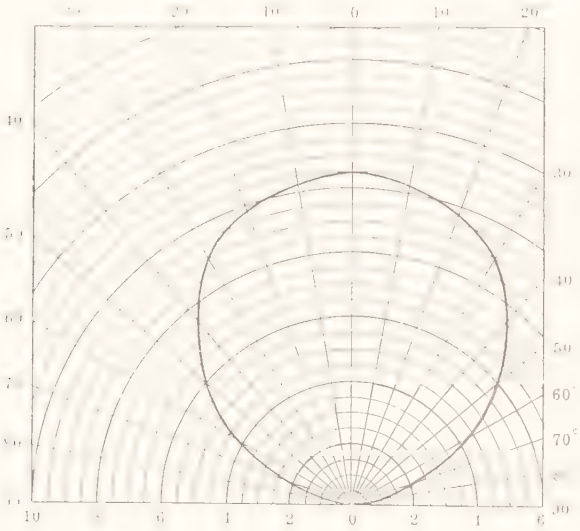

FIG. 24.—The symmetrical release of photoelectrons about the normal to the surface. (After Ives, by courtesy of the Physical Review.)

and more to follow the established lines of force. Since these lines are perpendicular to the cathode, the distorted distribution converges toward the normal. For a given geometry of electrodes between which a voltage is applied, a definite electrostatic field exists in which the electrons behave much the same as celestial planets do in a gravitational field. The actual path followed by any electron depends upon its initial direction of emis-

sion from the cathode, upon its initial velocity of egress, and upon the strength and geometry of the field. If the electronic emission becomes great, the presence of the free negative charges has an appreciable influence on the established field.

It has already been stated that for radiation of a given frequency electrons are liberated having velocities of emission ranging from zero up to a definite maximum determined by the frequency.

Measurements show that the *intial energies* are quite symmetrically distributed about a mean which is half the maximum. Of course the ultimate velocity and energy of an electron upon arrival at the anode is determined by the accelerating potential.

Influence of electrostatic fields. - If the strength of the electrostatic field at any point is H, then the force acting on an electron at the point is He. No matter how inhomogeneous the field may be, the total work expended on the charge while it is carried between the electrodes is Ve, where V is the value of the applied potential. The acquired energy is computed simply from the relation $\frac{1}{2}mv^2 = Ve$. If the electron was ejected with an initial velocity v_0, the final velocity is $\sqrt{v_0^2 + v^2}$. For a reverse polarity; that is, a retarding instead of an accelerating potential, the initial energy of the electron may be completely overcome and the charged particle driven back again to the cathode.

Influence of magnetic fields. The action of a magnetic field on an electron is quite different. In the first place, a magnetic field has no effect whatsoever on a charge not in motion. Secondly, upon a moving charge the acting force is directly proportional to the velocity of motion and takes place in a direction at right angles

both to the line of motion and to the direction of the field. The magnitude of the mechanical force on an electron moving with velocity v in a direction at an angle θ with the lines of force of a magnetic field H is

$$F = Hev \sin \theta.$$

When the electron travels at right angles to the field the force reduces simply to Hev. Furthermore, when it travels parallel to the field ($\theta = 0$), the force is zero.

For sake of clear mental images, it may be advisable to establish the absolute direction of motion of an electron in electrostatic and magnetic fields. It is obvious enough that because of the fundamental law of attraction of unlike charges and repulsion of like charges, a negative electron must travel in the sense of cathode to anode. A proton or any positive charge would travel in the reverse direction. An easy way to remember sense of motion in a magnetic field is to recall that a traveling negative charge is equivalent to a positive current in the opposite direction and hence, by Oersted's law, a moving electron is surrounded by a circular magnetic field with lines of force counterclockwise when viewed along the direction of travel of the electron. Thus when the negative charge passes into an established magnetic field, the charge will be caused to deflect toward the side where its own field partially neutralizes the established field. To illustrate, if a magnetic field existed directed into the plane of the paper, an electron initially traveling from left to right must be deflected downward.

Combined influence of both fields. It is quite possible to have electrostatic and magnetic fields existing together in the same space and both acting in their own

manner on an electron. Two cases of particular interest arise.[55] First, the electron is projected at right angles into a composite field of mutually parallel electrostatic and magnetic lines. The forces Xe and Hev will be practically independent, and the resultant acceleration will be the vector sum of the two separate accelerations. Second, if the electron is projected at right angles into a composite field with electrostatic and magnetic lines perpendicular to each other and to the initial path of the electron, the strength and sense of the fields may be adjusted so that their effects are exactly neutralized; but if the electron starts from rest, the equations of motion show that it will describe a cycloidal path precisely like a point on the rim of a wheel which is rolling on a level surface. Such composite fields have been used practically in determining the velocities of electrons and the ratio of charge to mass. In the normal application of photocells, only electrostatic fields are at present involved.*

Current-voltage relation. It is instructive to study the manner in which the anode-cathode current of a photocell depends on the value of the applied potential for a constant illumination. In general there will be a small current for zero external voltage because most of the electrons are released with an initial velocity which is sufficient to carry them to the anode. If the contact potential between terminals is in such a direction as to aid the escape of electrons from the cathode, there will be a current even against applied retarding potentials, until such retarding potentials become great enough not only to neutralize the contact voltage but

* Application of magnetic fields to the modulation of photoelectric currents is described in Chapter IX.

also to overcome the maximum energy of emission of those electrons released by the highest frequencies present in the light. For a contact potential which happens to oppose release of electrons from the cathode, whether a current will flow or not for zero applied voltage depends on the maximum energy of emission as compared to the contact potential. Assume for example that an opposing potential of 1 volt exists by nature of the materials of the electrodes, and also that the least work function is 1 volt. For a current to flow in spite of the retardation we should have

$$\tfrac{1}{2}mv^2 \equiv h\nu - P = Ve;$$

that is, the maximum energy, which is equivalent to a quantum of radiation of the highest frequency present decreased by the work function, must be greater than the work done against an electron by the retarding field. Substituting $h = 6.55 \times 10^{-27}$ erg-sec., $V = 10^8$ e.m.u., $P = 10^8$ e.m.u., $e = 1.59 \times 10^{-20}$ e.m.u., we obtain

$$\nu = 4.86 \cdot 10^{14}\ \text{sec}^{-1}.$$

This frequency corresponds to a wavelength of about 6200 Å. In this numerical example, there will be a current for zero applied voltage provided only there are wavelengths shorter than 6200 Å present in the radiation.

Now assume that the external voltage is gradually increased. More and more of the slower electrons will be drawn to the anode until for a rather definite voltage practically all of the electrons released by the given radiation will be captured and the anode-cathode current will not increase further, no matter how high the voltage may become. Figure 25 gives a typical current-voltage

curve for a high-vacuum cell. After the current fails to increase further, it is said to be *saturated*.

There are three important factors which influence the value of the saturation voltage. One is the accumulation of *space charges*. In cells having clear-glass walls, negative charges can cling to the insulating surface and create a permanent electrostatic field to oppose the release of other electrons from the cathode. Even the atmosphere of traveling charges has the same effect.

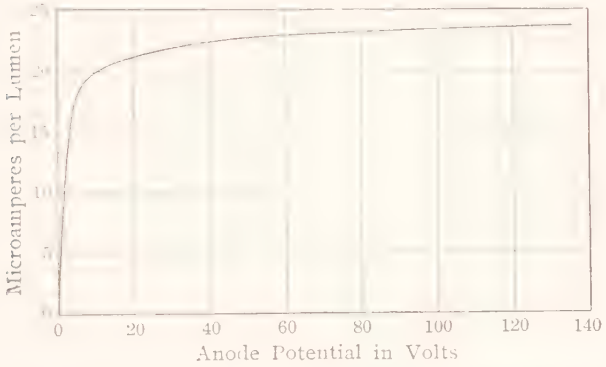

FIG. 25.—A current-voltage curve for a high-vacuum photocell.

Another factor is the *size of the collecting anode*. If the anode is relatively small in area, many of the electrons will not be strongly enough attracted by low fields and may shoot by in a perihelion arc. For an extremely small anode, the congestion of negative charges converging toward it forms an effective electrostatic barrier against more remote electrons. The third factor is the presence of *residual gases*, the effect of which will be discussed in the following chapter.

An obvious advantage of saturation in a photocell is the independence of the anode current with respect to

voltage. This means in practice that the voltage on the cell may vary within wide limits and still the current produced by a given flux of light will not change.

Current-light flux relation. Theoretically, the number of electrons released is exactly proportional to the intensity of the incident light. In a good vacuum cell, the actual anode-cathode current may be quite closely

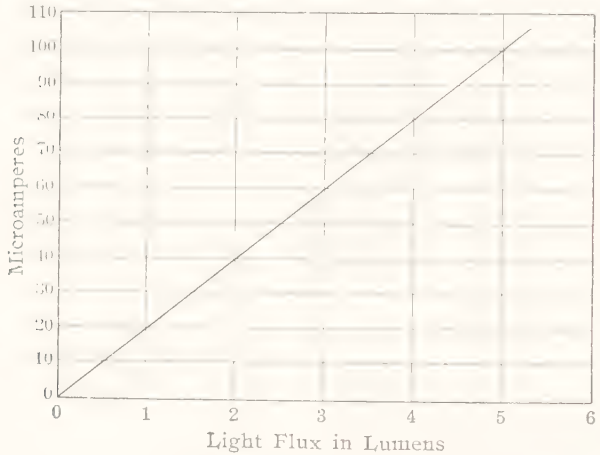

FIG. 26.—A current-illumination curve for a high-vacuum photocell.

proportional to the light flux entering the cell. Figure 26 illustrates such a relation from zero illumination up to 5 lumens, which, for the cell measured, corresponded to an intensity of about 750 foot-candles. The linear relationship in certain faulty cells may be masked or distorted by the existence of variable electric leakage or by a fatigue, either temporary or permanent, of the sensitive surface or again by a varying accumulation of space charges.

The exact linearity in suitable cells is a very valu-

able asset for photometry or for accurate reproduction of sound recordings on films or for similar requirements.

Dynamic characteristics. The electron has the least mass of any known object. Its mass is only about 9×10^{-28} gram or 2×10^{-30} lb. To realize how small this is, imagine an electron speeding through space at the rate of 100 miles an hour or about 150 ft. per second. Let us calculate the force of a blow it would give to an obstacle placed in its path, assuming the electron to be brought to a dead stop in one-tenth second. We have simply,

$$F = \frac{mv}{gt} = \frac{2 \times 10^{-30} \times 150}{32 \times 0.1} = 10^{-32} \text{ lb. approx.}$$

In other terms, the average force experienced by the obstacle would have the amazingly small value of one one-hundred-thousand-million-billion-trillionth of a pound.

A particle possessing such small mass will of course present no appreciable inertia to any applied force. Thus an electron, whose electrostatic charge is so large compared to its mass, starting with zero velocity at the cathode and traveling to the anode under a field of one volt will acquire a velocity of nearly 6×10^7 cm. per sec., which is equivalent to 25,000 miles an hour.

All experience has shown that photo-emission takes place almost instantaneously.[7] No one has ever been able to measure a lag between the incidence of the light and the issuance of the electrons. In a high-vacuum cell, a fluctuating light causes the numbers of emitted electrons to vary in exact correspondence. The alternating component of the current flowing through the cell is called the *dynamic response*. For sake of definition,

it is customary to measure the dynamic response of a cell for a sinusoidal light flux at a frequency of 1000 cycles per second. Although absolute measurements are difficult to make, especially for frequencies above 10,000 cycles, results consistently indicate that *the dynamic response of a vacuum cell does not vary with the frequency of modulation of the incident light.*

In present-day applications such as talking movies and television in which the alternating component of the photocell current is the desired output, dynamic response is vastly important.

Note that dynamic response implies fluctuation of light and not of terminal voltage. If alternating voltage is impressed between the electrodes, the cell behaves as an efficient rectifier and the current resulting from steady illumination consists of unidirectional pulsations of the same frequency as the impressed voltage. Varying the intensity of the illumination then produces fluctuations in current superimposed on the pulsations. For frequencies of voltage higher than about 50,000 cycles, the electrostatic capacity of the cell becomes appreciable and a capacitance current is added to the other two. Naturally, the capacitance becomes more important the weaker the light flux into the cell.

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CHAPTER VI

THE GAS-FILLED PHOTOCELL

Because even the most sensitive vacuum cells pass a relativity small current for a given flux of light, it has been the almost universal custom to employ gas-filled cells in all devices which demand a greater effective sensitivity because of the so-called *gas amplification* of the primary photoelectric emission. But the gas cell, as we shall term it, has certain characteristics so different from those of the vacuum cell that it will be well worth while to consider them in detail. First of all we must make ourselves familiar with the nature and behavior of gases in general.

Kinetic theory of gases.—Imagine a closed vessel containing gas, let us say a monatomic gas. We must picture the atoms as darting about at speeds of the order of a mile a second, suffering innumerable collisions with one another and with the containing walls. The impacts upon the walls are the sole cause of outward pressure experienced by the vessel.

Many laws have been formulated to describe the mechanical behavior of gases but most of them are included in the general law.

$$PV = RT$$

where P is the pressure, V is the volume, T is the absolute temperature, and R is a constant practically identical for all gases. Evaluated for one molecule, $R = 1.372 \times 10^{-16}$.

A remarkable relation deduced by Avogadro is that for a given pressure and temperature all gases have the same number of molecules per unit volume. At 0° C. and atmospheric pressure (760 m.m.) Avogadro's number is 2.70×10^{19} per cubic centimeter.

Imagine 1 gram of gas in the vessel kept at room temperature. If the vessel should be made smaller, there would be a greater density of gas, resulting in more collisions per second per unit of surface, and hence the pressure becomes greater. Again, let the temperature be raised. The kinetic energies of the atoms increase and the collisions become more frequent and more violent against the walls, producing an increase of outward pressure.

Ionization in gases.—We are interested particularly in the electrical behavior of a gas. In a given volume of gas between two electrodes there are always at least a few free electrons. When a potential difference is applied across the electrodes, these electrons begin to accelerate toward the anode. If the voltage is great enough and the electron has an unobstructed path long enough to permit it to acquire a definite minimum kinetic energy, it will cause an external electron to be liberated from the first atom with which it efficiently collides. Both electrons will then accelerate further toward the anode and each in turn can free another electron and so on in geometrical progression until the ultimate rate of recombination of electrons with the robbed atoms outside the discharge path equals the rate of liberation. Then the electronic current may reach equilibrium. In the meantime some of the bereft atoms, possessing a residual positive charge, begin to gather momentum in the direction of the cathode. Again if conditions are favorable,

they can also liberate electrons which in turn free successively one electron after another in their frantic jostling on the way to the anode. If the atoms are relatively close together, many slowly moving electrons may attach themselves to neutral atoms and produce a negatively charged particle which will move toward the anode. Any atom or group of atoms which possesses a residual charge due to the removal or addition of one or more electrons is called an *ion,* and the process of producing the charge, especially by removal, is called *ionization.* It is quite evident from the above qualitative discussion that what will occur within the gas will depend upon a number of factors, chief of which are: applied potential, distance between electrodes, number of atoms per unit volume (usually measured by the pressure of the gas), and the nature of the gas itself.

The last point determines the minimum kinetic energy required to liberate an external electron from the atom.

The potential through which an electron must fall in order to acquire sufficient energy barely to release an electron from an atom is termed the *ionizing potential* of that atom. Table 4 records the ionizing potentials for a number of gases.

TABLE 4

IONIZING POTENTIALS FOR SEVERAL GASES

	Volts	
Hydrogen	13.3	(Mohler and Foote)
Helium	25.6	(Foote and Mohler)
Neon	21.5	(G. Hertz)
Argon	15.1	(Foote and Mohler)
Krypton	13.3	(G. Hertz)
Xenon	11.5	(G. Hertz)
Nitrogen	16.9	(Foote and Mohler)
Oxygen	15.5	(Foote and Mohler)

Mean free paths. – In a gas at a definite pressure and temperature, the atoms, on the average, will suffer a definite number of collisions per second or per centimeter of travel. As the pressure is reduced by actual removal of atoms from the space, the average path traveled before collision occurs becomes longer. A point will be reached with lower pressures when the average unobstructed travel becomes longer than the distance between opposite walls (or electrodes) and then presence of neighboring atoms becomes unimportant so far as ionization is concerned. The average path between collisions for any given condition of a gas is called its *mean free path.* It seems quite reasonable that the mean free path is inversely proportional to the pressure of the gas. Because the electron is so small in size compared to an atom of gas, its mean free path is longer than for the atoms themselves. It has been shown that for an electron the path is $\lambda = 1/\pi r^2 n$, where r is the radius of the atom and n is the number of atoms per cubic centimeter.

It should be clear that even in so-called "high-vacuum" devices, the vacuum characteristics are not due to the fact that all the molecules of gas are absent, but rather to the fact that the mean free path is so great compared to inter-electrode spacings that the probability of collision is small. For example, in the high-vacuum photocell, the degree of evacuation can scarcely be made less than 10^{-6} mm. of mercury. The corresponding mean free path for molecules is about 7000 cm., and for high speed electrons about 400 meters. The number of molecules still remaining in such a vacuum is of the order of several billion per cubic centimeter.

Optimum pressures. It is interesting to note that for a given gas with ionizing potential V_0 and for a given applied voltage gradient X, there is a pressure at which maximum ionization occurs and hence at which the current carried between electrodes is a maximum. First experimentally established by Stoletow and later confirmed by theory, the expression for the optimum pressure is

$$P_{\max} = k \frac{X}{V_0},$$

where X is the field strength at any point. In the simple case of a uniform field between parallel plates at a distance d from each other, the field strength is $X = V/d$.

Suppose that at the cathode n_0 electrons are released per second by radiation. It has been shown by Partzsch [1] that for the optimum pressure, the number of ions arriving per second at the anode is

$$n = n_0 e^{\frac{V - V_0}{V_0 e}}$$

where both e's are the base of natural logarithms.

Both these equations are restricted to the assumption that conditions are not favorable to the production of extra ions by positive ion bombardment. When this happens, the current increases very rapidly and, if there were no limiting resistance in the circuit, the current would become very large.

The curve shown in Fig. 27 is typical of the dependence of total current in a gas cell upon applied voltage for a constant illumination. The pressure of the gas is of the order of 100 microns.* At this pressure, the

* A micron is a unit of pressure equivalent to that produced by a column of mercury one-millionth of a meter in height.

mean free path of high-speed electrons in argon gas may be roughly computed. We may take for the radius of the argon atom 1.92×10^{-8} cm. The number of atoms per cubic centimeter may be found from Avogadro's number 2.70×10^{19} reduced to a pressure of 100 microns by use of the general gas law which states implicitly that for a given volume the density of the

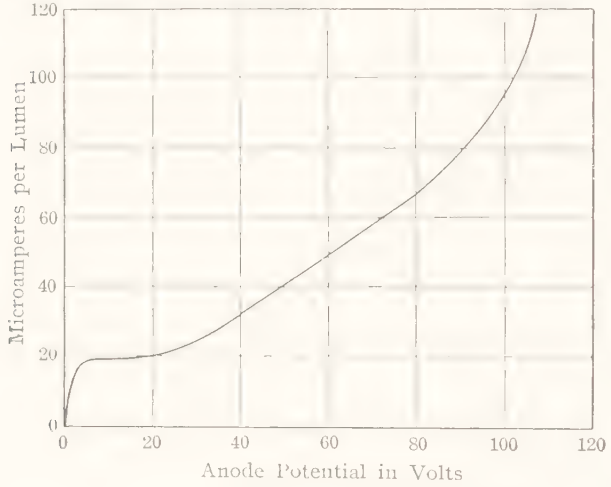

FIG. 27.—A current-voltage curve for a gas-filled photocell.

atoms is inversely proportional to the pressure. Thus the number of argon atoms per cubic centimeter at 0° C. is

$$n = 2.70 \times 10^{19} \times 0.1/760 = 3.5 \times 10^{15}.$$

Then,

$$\lambda = \frac{1}{\pi r^2 n} = \frac{1}{3.14 \times (1.92 \times 10^{-8})^2 \times 3.5 \times 10^{15}}$$
$$= 0.24 \text{ cm}.$$

If an electron is to ionize an atom at the end of this path, it must acquire within the distance an energy equivalent to the ionization potential, about 15 volts. In other words the field strength must be about 60 volts per centimeter. Of course many electronic free paths are longer than the mean path and ionization will actually begin at lower voltage gradients. Again, when the field is not uniform, as for example, with a semi-cylindrical cathode and an axial anode, the field will be much stronger near the anode and ionization will begin sooner than the average gradient would account for. Obviously, for a given applied voltage the actual field strength at a point depends on the size and shape of the electrodes and on the distance between them.

L. R. Koller [7] has published curves, reproduced in Fig. 28, illustrating the effect of gas pressure upon the effective sensitivity of a given photocell. Note that as the pressure decreases from 8 mm., the current-voltage curves acquire steeper slopes in the range 70 to 90 volts until a pressure of 0.2 mm. is reached after which the slopes again decline. The physical explanation implicit in Stoletow's law is that for the higher pressures the electrons generally suffer collisions before they have acquired sufficient energy to ionize. At the lower pressures, many electrons travel clear to the anode without colliding with atoms. For intermediate pressures, the electrons collide as a rule just as soon as sufficient energy for ionization has been attained. The practical significance lies in the fact that for the optimum pressure, maximum current proportional to the number of electrons released at the cathode by the existing light can be caused to pass through the cell before reaching the condition in which positive ions release sufficient extra

electrons at the cathode to regenerate the ions. When this condition is reached, the gas breaks down into a glow as in a Geissler tube, and the glow will continue even when the exciting light is removed.

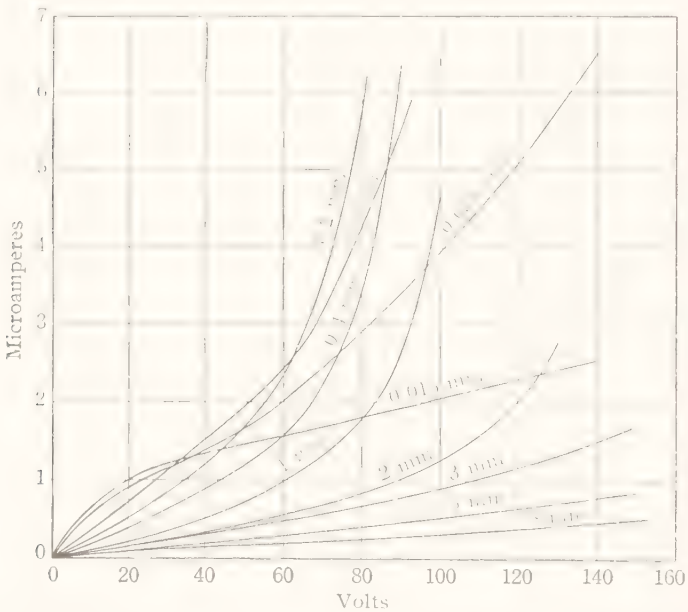

FIG. 28.—The effect of gas pressure on the maximum sensitivity of a photocell. (After Koller, by courtesy of J. O. S. A. and R. S. I.)

Limitation in gas amplification. The phenomenon of glow discharge in gas cells limits the amount of gas amplification that may be utilized. The ratio of the total ionization current to the electronic current from the cathode should not be greater than 10 as a maximum, if the cell is to be operated in a fairly stable condition.

It has been recently observed that part of the amplification previously attributed to ionization of the inert

gas between the electrodes is really due to the ejection of secondary electrons from the cathode by the bombardment of positive ions. The energy required to release an electron from the sensitive surface is much less than that required to release an electron from an atom of the gas, and hence the positive ions can eject electrons at the cathode at relatively low velocities. The secondary electrons will in turn produce fresh positive ions plus other electrons, and the breakdown of the gas will occur at a lower voltage than if gaseous ionization alone produced the amplification.

The gas cell is not so linear in its response to light of varying intensity as is the vacuum cell, the difference being that the current increases more than in proportion to the increase of light, as illustrated in Fig. 29. However, the linearity is quite good enough to obviate any appreciable distortion in the reproduction of music recorded in such a manner as to modulate the intensity of the light incident on the cell.

For photometric work, linearity cannot be assumed except for small ranges of intensity depending on the accuracy required. It is to be noticed from Figs. 27 and 29 that the linearity is best not only for relatively low intensities, but also for lower voltages. Perhaps the explanation lies in the secondary action of positive ions. Either an increase in voltage or an increase in number of original electrons causes the positive ion action to become more pronounced and the effect multiplies itself in a quasi-regenerative fashion. Of course, if the voltage is made too high, the regenerative action will occur in the role of gaseous ionization by positive ions.

Dynamic characteristics. Whereas the vacuum cell follows fluctuations of light intensity with great fidelity,

the gas cell has a variable dynamic sensitivity which always decreases with increased frequency of light modulation. Figure 30 shows the relative dynamic response of a gas cell for a wide range of frequencies and for different values of applied voltage. Observe that the

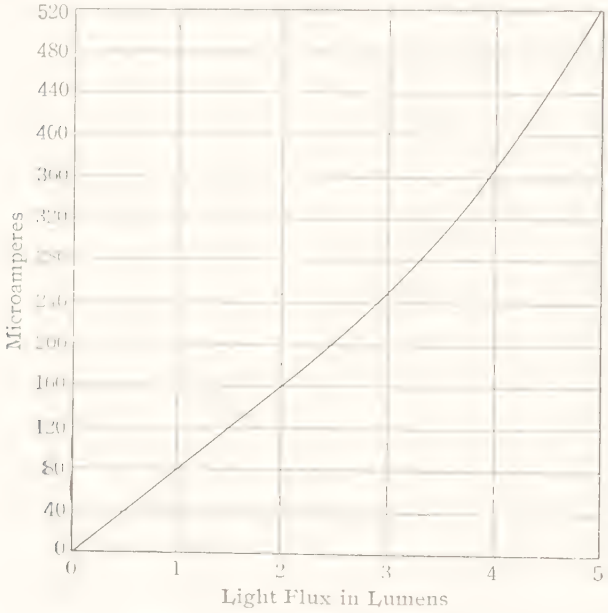

FIG. 29.—A current-illumination curve for a gas-filled photocell.

most rapid decrease occurs over the first 1000 cycles and that the response continues to decline rather uniformly up to 50,000 cycles; also that the effect is greater for higher voltages. The reason for the dropping off with frequency can be found again in the secondary functioning of positive ions. The rate of thermal diffusion of positive ions to the walls of the tube is of the order of 10^4 cm. per second. Thus a finite interval occurs after

the light flux is diminished during which ions are still traveling toward the cathode. Upon striking the cathode new electrons would be liberated, which would add to the electronic current just as much as though they were photo-electrons. The effect would be for the current to be prolonged even after the light has been reduced to zero. Obviously, as the frequency of light impulses increases, the change in current becomes

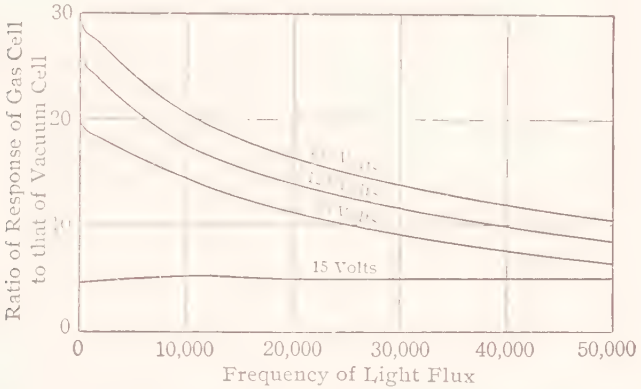

FIG. 30.—The dynamic response of a certain gas-filled photocell at various voltages.

smaller; and it is change in photo-current which constitutes the dynamic response. It might be said that a gas cell acts inductively to light pulsations, tending to maintain the current for decreasing light and lagging behind an increasing intensity.

For higher voltages, ionization plays a more important role in the total photo-current and hence the inductive effect must be greater. For voltages which are quite low, most of the current is electronic, and conditions approach those met with in a vacuum cell.

It is worth noting from Figs. 27 and 30 that at 15 volts the gas cell is equivalent to the vacuum cell in three respects: (1) *current is saturated so that it is independent of small variations in voltage;* (2) *the sensitivity is of the same order of magnitude;* (3) *the dynamic response is independent of frequency of modulation.*

The curves in Fig. 30 were obtained in the following manner. As a source of light a neon glow tube was employed in which the glow was concentrated in a small central crater. If such a tube has a sufficiently high voltage applied to break down the gas into a glow, the intensity of the discharge will depend upon the current passed. If the current is caused to fluctuate, the light from the glow fluctuates in exactly the same manner.

The output of an audio oscillator generating sine wave voltage at calibrated frequencies was fed into an amplifier which in turn supplied the potential for the glow tube. The circuits were so devised that a definite direct current could be sent through the tube and, superimposed, also a definite alternating current of a known frequency. The fluctuating glow was caused to shine into a photocell which was coupled to an amplifier and meter. Only changes in photocell current could pass through the amplifier; the steady current in the cell had no effect on the meter reading. Thus a response curve was first taken with a high-vacuum cell and then with a gas cell under exactly the same conditions of operation of the glow tube. Dividing the readings for the gas cell by corresponding readings for the vacuum cell eliminated any characteristic distortions due to the glow tube or to amplifiers. Strictly speaking, the curves represent the ratio of the dynamic response of the vacuum cell to that of the gas cell.

Gases used in photocells. Because the alkali metals are so active chemically, it is quite necessary to employ an inert gas for amplification by ionization. There are only five truly inactive gases; *helium, neon, argon, krypton* and *xenon.* All of these gases were actually separated and identified within the brief space of four years during the last decade of the nineteenth century. Helium, which is only one-fourth as heavy as oxygen and which is now familiar as filler for American dirigibles, is not frequently employed in gas photocells because of its relatively high ionization potential, as seen in Table 4. This gas was first detected spectroscopically in the solar spectrum by Lockyer [59] in 1868, and obtained its name from the Greek word for sun. It was first physically separated from a mineral in 1895 by Ramsay.[60] Now it is derived principally from certain natural gas wells in the United States.

Neon, brought to public notice by its use in the brilliant red electric signs, serves satisfactorily in photocells. However, it is fairly expensive since it forms by volume only about 0.002 per cent of the air from which it is obtained. Neon is used quite extensively in glow tubes for television receivers. It is somewhat heavier than oxygen.

Argon comprises as much as 1 per cent of the air, from which it is separated with relative ease. Because of its abundance and more especially because of its very low ionization potential, it is almost universally employed in photocells. Argon was the first inert gas to be isolated, credit being due to Rayleigh and Ramsay [61] in 1894. The only disadvantage of argon is the mass of the atom, for it is more than twice as heavy as oxygen. This fact is partly responsible for the decrease of dynamic sensitivity noted above.

In 1898 Ramsay and Travers [62] identified successively from residues of the evaporation of liquid air the gases krypton, xenon and neon. The detection was always by means of observing new spectroscopic lines. Krypton and xenon, two very heavy gases, are so rare that they have not been put to any practical use.

Helium, argon or neon may be conveniently purified to the extent required for its admittance to photocells by storing in a glass container provided with calcium electrodes between which an arc is formed. The calcium reacts with any contaminating impurities.

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CHAPTER VII

PHOTO-CONDUCTIVE AND PHOTO-VOLTAIC CELLS

Although this text is primarily concerned with the phenomenon of photo-emission, it would not be complete without at least a brief reference to *photo-conductive* and *photo-voltaic* cells.

I. PHOTO-CONDUCTIVE CELLS

Photo-conduction — that is, change in electrical resistance of a body due to the action of incident light—was first intelligently observed by Willoughby Smith [1] in 1873. Tiny rods of selenium, which he was using as high-resistance elements in an experimental circuit set up at a transatlantic cable station, were found to become much better conductors of electricity when exposed to daylight or to any artificial illumination.

The element selenium. Selenium is a chemical element which lies on the borderland between conductors and insulators. In the periodic table (see Appendix) it lies between the metal tellurium and the non-metal sulphur. Under any condition selenium is a very poor conductor, but its difference in conductivity when in the dark and when illuminated provides a most interesting and valuable property.

Selenium was discovered by J. J. Berzelius [2] in 1817. This chemist succeeded in separating the element from

the dregs accumulating from a certain process of manufacturing sulphuric acid. Since that time all the properties of the "moon-element" have been investigated. It is known to exist in several allotropic forms, only one of which—grey crystalline—shows the photo-conductive effect in appreciable magnitude. Table 5 gives some of the more important physical constants of selenium.

TABLE 5

PHYSICAL CONSTANTS OF SELENIUM

Atomic weight	79.2
Melting point	217° C.
Boiling point	690° C.
Specific resistance	70,000 ohms (crystalline)

Dozens of different forms of selenium cells have been devised to take advantage of its photo-conductive property. Since it is quite opaque, light cannot penetrate to any great depth, and hence it becomes a chief object in design to expose as much surface as possible to irradiation without making the resistance too great. Aside from this point, the essential structure of any selenium cell comprises simply two electrodes joined by the semi-conducting element.

The selenium cell. A very practical low-resistance cell consists of electrodes in the form of two insulated but closely interpenetrating grids of gold on glass, similar to Fig. 31, with a thin film of selenium bridging the gaps. The selenium may be distilled onto the glass or painted on in solution. It must then be annealed at a temperature near its melting point until it all is converted to the grey crystalline variety. The finished mount should then be sealed into an evacuated bulb with two wires leading out from the two electrodes.

If such a cell is placed in the dark with an applied voltage and meter in series, the meter will register a

FIG. 31.—A simple type of structure for a selenium cell.

current, indicating that normal selenium is a poor conductor. If now light is suddenly made to shine into the cell, the current will increase rapidly at first and then more slowly until a maximum value is reached. If the light is suddenly turned off, the current decreases rapidly

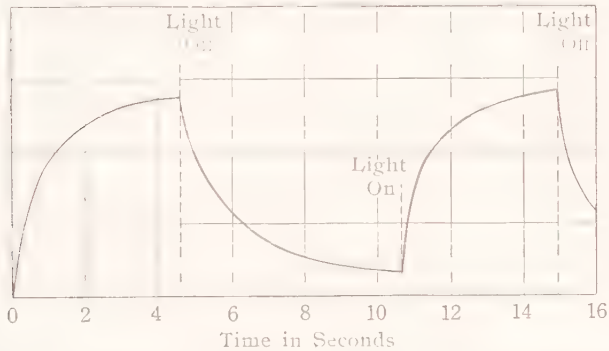

FIG. 32.—The nature of the response of a selenium cell for intermittent illumination.

at first and then more and more slowly until ultimately only the original dark current is flowing. It may require several minutes for the original value to be reached. This typical action of selenium is illustrated in Fig. 32.

Mechanism of conduction. The probable effect of the light is to liberate electrons within the selenium. However, as these electrons travel through the substance, some of them reunite with positive ions to produce neutral atoms again. This means that sooner or later an equilibrium must be reached between the rate of release of electrons and the rate of recombination, so that a maximum value of conductivity will be reached. Similarly, upon removal of the light, recombinations at first rapidly reduce the number of free electrons present, but as the number decreases, so does the probability of recombination, and the electrons dwindle only asymptotically to the normal average number.

Laws of photo-conduction. These assumptions not only account for the lagging characteristic of selenium but also predict how the maximum response must vary with the intensity of illumination. D'Albe [65] has shown that the *current due to the light should depend upon the square root of the intensity of the light.* If, however, there is a limitation to the number of ions that can be formed in a given region of the selenium, the current will increase in a still smaller ratio. The square-root law is approximately obeyed in the actual illumination response curve of any commercial cell.

Referring to Fig. 32, we can observe that the first part of the curve is practically linear before equilibrium and maximum current is approached. This leads one to a second important law of photo-conduction. For short intervals of illumination, the current is proportional to the product of the intensity and the time of exposure. This may also be stated: *For rapidly fluctuating illumination, the current is proportional to the intensity and inversely proportional to the frequency of*

fluctuation. This effect is obtained by working on the unsaturated part of the curve, the conductivity between flashes depending upon the number of electrons liberated during a flash. Of course, the greater the frequency of the flashes, the fewer electrons liberated during each flash.

Dynamic response. Due to its inherent sluggishness, selenium cannot follow the actual change in intensity occurring in sinusoidal modulation of the incident light, and its inability to follow becomes more apparent with increasing frequency of modulation. This means that the dynamic response of a selenium cell will be of a lower order of magnitude than its static response or its peak response for pulsating light, and that it will fall off rapidly with the frequency. Nevertheless, because of its relatively high photo-conductive sensitivity, it is still possible to use such a cell for the reproduction of speech and music. The quality is rather smooth and mellow, due to the high-frequency cut-off.

Color sensitivity. Like the photo-emissive cell, the selenium cell has a color sensitivity characteristic. Curve *a* in Fig. 33 gives the actual response of a commercial cell to the different colors as they are emitted by an ordinary incandescent lamp and dispersed by a prism. Curve *b* is the response of the same cell reduced to unit energy of incident radiation. The latter curve indicates that selenium is most sensitive to violet light in the visible region and secondly to red light. However, it responds in a certain degree to all colors.

Later work has developed structures of selenium cells which have less lag than the cruder, older types. Also clever methods have been devised for minimizing the lag, such as the employment of blue light instead of white

or the use of the differential effect between two cells of similar characteristics, but of different sensitivities.

Thalofide cell. Other substances beside selenium have been found to be photo-conductive. T. W. Case [66] has prepared a compound known as *thallium oxysulphide*, which is quite sensitive to the red and infra-red, having a maximum at about 10,000 A. The commercial cell prepared from this compound is known as a thalofide cell. It enjoys an important usage in one system of

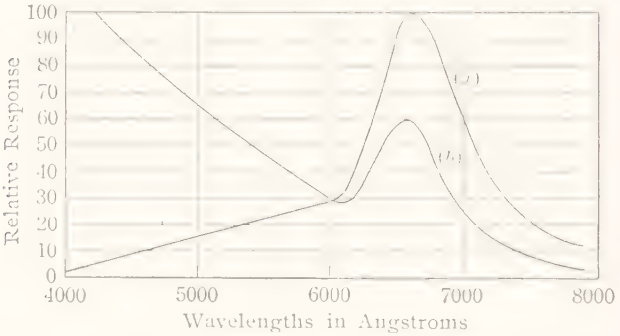

FIG. 33.—(*a*) Response of a selenium cell to various colors as emitted by a lamp and dispersed by a prism; (*b*) color-sensitivity curve for the same cell.

talking pictures. The cell is ordinarily protected by a special light filter to minimize the rate at which the sulphide changes with exposure into an insensitive sulphate.

II. PHOTO-VOLTAIC CELLS

The photo-voltaic effect, otherwise known as the *Becquerel effect*, consists in the creation of an electromotive force in an electrolytic cell when either an electrode or the electrolyte itself is exposed to illumination. Photo-voltaic cells with sensitive electrolytes such as

solutions of uranyl or uranous salts are at present of little practical interest, whereas cells with a sensitive electrode are meeting with commercial success.

The most common substances used for electrode surfaces are the *silver halides* and especially *cuprous oxide*. If a simple cell is made up with two copper electrodes similarly coated with cuprous oxide and immersed in an electrolyte of almost any nature, the potentials set up between the electrodes and the electrolyte will be equal and opposite so that the external electromotive force will be zero and no current would flow if the two electrodes were externally connected. However, if one of the electrodes is illuminated, an extra voltage is created, which may be measured. Investigations made by H. Garrison [67] revealed that the normal effect is the production first of a negative potential which quickly reverses with continued illumination and finally reaches equilibrium in a positive sense. He found that the maximum negative photo potential was proportional to the intensity of the light for low illumination and tended to reach a constant value for high intensities. The maximum positive potential varied approximately as the logarithm of the intensity. The maximum effect he was able to observe was a value of 0.30 volt when the electrode was illuminated by a 500-cp. lamp at a distance of 25 cm., an intensity corresponding to about 725 foot-candles.

Photo-voltaic cells.—One of the commercial photo-voltaic cells, known to the trade as *Ruggioto*, consists of a cathode made of a semi-cylindrical plate of copper uniformly coated with cuprous oxide and an anode made of lead in the form of heavy strip. The electrolyte is a dilute solution of lead nitrate. The whole is contained

in a glass cylinder closed at both ends with bakelite blocks. The circuit recommended is shown in Fig. 34.

Fig. 34.—The circuit recommended for the Rayfoto cell.

The curves of Fig. 35 show the remarkable sensitivity of the unit. The current through the external circuit is linear with respect to illumination and amounts to an appreciable fraction of a milliampere for the rather reasonable intensity of about 100 f.c. This current is quite sufficient to operate a sensitive relay.

Naturally this sensitivity is of the static type. The writer's experience indicates that the rate of change of voltage is quite sluggish for fluctuating light. Claims have been made that photo-voltaic cells can be made to respond to audio frequencies of light modulation, but certainly the dynamic response is much

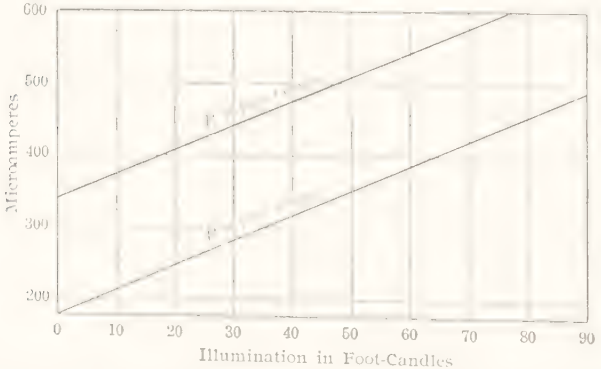

Fig. 35.—Linear response of a commercial photo-voltaic cell for various illuminations.

poorer than that of the selenium cell and cannot be compared to that of even a gas-filled photo-emissive cell.

There is another type of photo-voltaic effect which is not chemical in nature. W. W. Coblentz[68] has brought attention to the fact that certain crystals of *molybdenite* have the property of developing a potential difference of a few microvolts when illuminated. The dynamic response is much superior to that of the photo-conductive selenium.

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CHAPTER VIII

THE PHOTOCELL CIRCUIT AND THE RADIO TUBE

Even the very best gas-filled photocells yield currents only as great as 100 microamperes per lumen of light flux. Many types of cells may yield only one-hundredth to one-tenth this amount. In many applications, where commonly less than a tenth of a lumen is available because of the essential optical definition, the current flowing in the cell may lie in the range 0.01 to 0.1 microampere. Quite obviously, so small a current is incapable of operating directly a loud speaker or a television receiver. Hence it becomes necessary to amplify photo-currents many thousands of times before they can be satisfactorily utilized.

Elementary photocell circuit.—No matter what the nature of the amplifier may be, the photocell must be introduced into some sort of electric circuit. Let us then first of all consider the elementary theory involved in a simple circuit.[69] The diagram in Fig. 36 shows the cell in series with a load resistance Z_0 and an electromotive force E. We wish to find an expression for the instantaneous

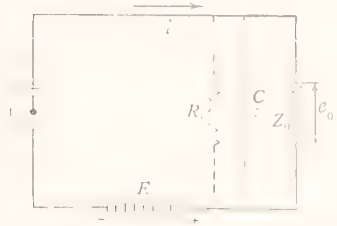

FIG. 36.—An elementary photocell circuit.

current, i, and the voltage drop, e_0, across the load. If the value of the variable light flux is l, and the sensitivity of the cell is S, by definition we have, $i = Sl$. Now S is in general a function of the anode voltage, e_a, but in the case of a vacuum cell operated above saturation voltage, S becomes independent of e_a, and hence $e_0 = iZ_0 = SZ_0l$. For frequencies of light modulation small enough that the capacitance of the circuit is negligible, the output from the vacuum cell circuit will be directly proportional to the intensity of the light.

If a gas-cell is employed, S will vary with change of anode voltage. Obviously, from the circuit of Fig. 36, $e_a = E - iZ_0$. Let us assume that the variation of intensity of light flux is small enough that we may consider the cell as operating on a linear portion of its current-voltage characteristic. Then the sensitivity can be expressed as $S = S_0 - ge_a$, where S_0 and g are constants. To evaluate S_0, let $S = S_0$ when $e_a = E$.

Then $$S_0 = S_1 - gE$$

and $$S = S_1 - g(E - e_a).$$

But $$E - e_a = Z_0i.$$

Therefore, $$S = S_1 - gZ_0i.$$

Finally, $$i = Sl = (S_1 - gZ_0i)l$$

or, $$i = \frac{S_1l}{1 + gZ_0l}.$$

Let us now define the *conductance* of a photocell as $G = di/de$; that is, G is numerically equal to the slope of the current-voltage curve. Similarly S may be defined mathematically as di/dl, the slope of the current-illumination curve. By comparing definitions, we find

that $dS\ de = dG/dl$. But by the assumption $S = S_0 + ge_a$, $dS/de = g$. Thus $g = dG/dl$, and is defined as *conductance per lumen*.

If we assume that l is undulating in a sinusoidal manner represented by the relation $l = \frac{1}{2}L(\sin \omega t + 1)$, we can derive an equation for current of the form *

$$i = \frac{S}{gZ}\left[1 - \frac{2}{a}\sum_{n=0}^{n=\infty}\left(\frac{bj^2}{a}\sin \omega t\right)^n\right],$$

where $b = gZ_0l$; $a = b + 2$; and $j^2 = -1$.

Furthermore, since $e_0 = iZ_0$, we may write

$$e_0 = \frac{S_1Z_0l}{1 + gZ_0l},$$

which is the desired equation for the voltage drop across the load; and if this potential is introduced into an amplifier, it is referred to as the voltage output of the photocell circuit. It is apparent that e_0 is not directly proportional to l, but is related in a hyperbolic manner. Assuming $S_1 = 90$ microamperes per lumen, $Z_0 = 3$ megohms, and $g = 10^{-6}$ mho † per lumen, Fig. 37 illustrates how e_0 depends on l. Because the curve is not a straight line, if l varies in a sinusoidal manner, in addition to the fundamental frequency there will also be harmonics. It is important to know how prominent the second and third harmonics will be for given parameters in the circuit. Using the value for i in the form of a Fourier series, we can express e_0 as

$$e_0 = \frac{S_1}{g}\left[1 - \frac{2}{a}\sum_{n=0}^{n=\infty}\left(\frac{bj^2}{a}\sin \omega t\right)^n\right],$$

* See Appendix for mathematical derivation.

† A mho, or reciprocal ohm, is the unit of conductance. A conducting system whose resistance is one ohm has a conductance of one mho.

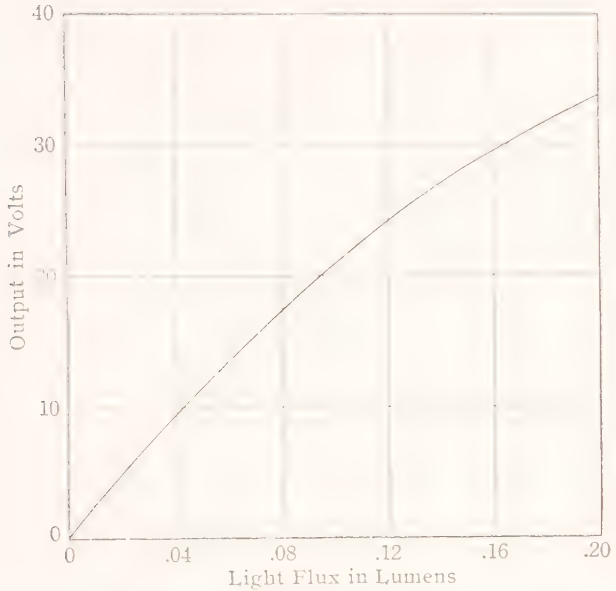

FIG. 37.—The calculated output of the elementary circuit is not truly linear for a gas-filled cell.

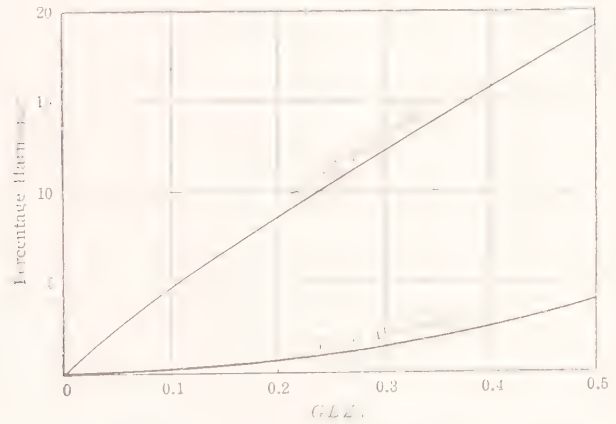

FIG. 38.—Harmonics present in the output of the elementary circuit for a gas-filled photocell. (After Metcalf, by courtesy of Proc. I. R. E.)

Fig. 38 is a graphic representation of the relative amplitudes of second and third harmonics plotted as percentages of the amplitude of the first harmonic or fundamental for various values of the product gZ_0l.

Effective impedance. Examination of the expression for e_0 also reveals that the voltage output increases together with Z_0. Hence, it would appear that Z_0 should be made as large as possible. However, there are two limiting factors which prevent the load from being increased beyond a certain optimum value. In the first place, the constant small ohmic leakage between all points at different potentials becomes more and more important as Z_0 increases. Secondly, electrostatic capacity between parts of the circuit acts more and more as a shunt to Z_0 when l is fluctuating so that corresponding variable fields are produced in the circuit. Representing the leakage by R_0 and the capacitance by C_0 as shown by the dotted lines in Fig. 33, the effective value Z of the load impedance may be determined from the relation,

$$\left(\frac{1}{Z}\right)^2 = \left(\frac{1}{Z_0}\right)^2 + \left(\frac{1}{R_0}\right)^2 + (\omega C_0)^2$$

or

$$Z = \frac{Z_0 R_0}{\sqrt{Z_0^2 + R_0^2 + (\omega C_0 Z_0 R_0)^2}}$$

in which ω is the fundamental frequency of fluctuation. Therefore it becomes quite important in designing a photocell with accompanying circuit to make leakage resistance as great as possible if the output is to be efficiently large, and also to reduce capacitance to a minimum if fidelity of output is to be maintained at high frequencies.

Neglecting the effect of R_L, Fig. 39 illustrates the effect of C_0 upon the effective value of Z_0 for different values of frequency in herz or cycles per second. The value of C_0 assumed is 100 mmfd., which is a value quite easily obtained when even short extension cables are used as leads from the cell.

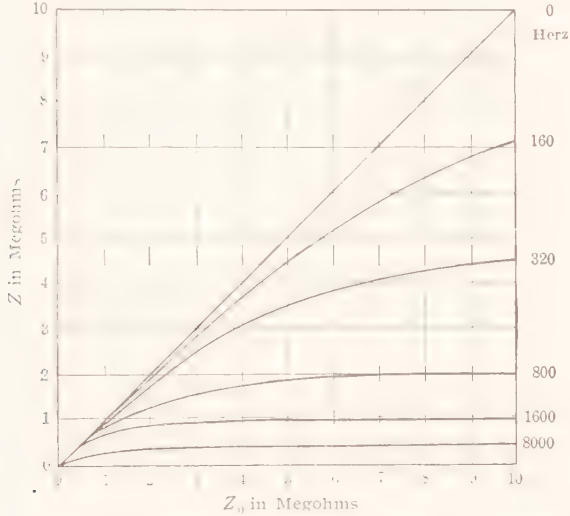

FIG. 39.—Decrease in effective impedance for various frequencies, due to a shunting capacitance.

In practice Z_L is usually a pure resistance, but examples of other types of load impedance will be discussed later.

The thermionic tube. In the amplification of the output of photocell circuits, the thermionic tube plays such an important role that it is well worth while to consider briefly the fundamental principles of its construction and operation.

The functioning of the tube depends primarily upon

the emission of electrons from a filament in the tube which is heated by an electric current. Such emission due solely to temperature effects is called thermionic emission. If we consider the rate of emission from a *tungsten filament* at normal operating temperature as unity, the emission from a *tungsten filament impregnated with thorium* will be roughly 10 and the emission from the more common types of *filaments coated with oxide of barium and strontium* will be about 100. J. Becker [70] asserts that oxide-coated filaments may emit as much as 1 ampere per square centimeter. Formerly it was the custom always to employ a source of direct current for exciting a filament, but since the demand has arisen for filaments of greater total emission and hence more power consumption, the practice has developed of employing alternating current supplied from step-down transformers. To avoid disturbances arising from temperature changes due to the nature of the oscillating current, an emitting element of the oxide-coated type may be made with relatively large heat capacity and be heated indirectly by means of an internal filament electrically insulated.

In the simplest structure, a thermionic tube may contain only two elements; the emissive filament and a collecting anode, called the plate, usually in the form of an elliptical or circular cylinder surrounding the filament. A conventional diagram is given in Fig. 40. The filament is heated by the battery *A*. Potential is supplied by the battery *B*. The electrons

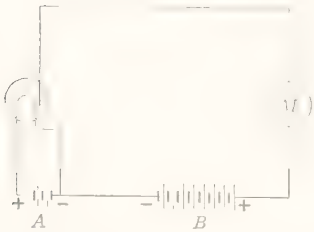

FIG. 40.—A simple circuit for a two-electrode thermionic tube.

streaming from filament to plate complete the electrical circuit through the meter M which registers the value of the current.

Laws of thermionic emission. Figure 41 show show the current depends upon the plate potential. For negative potentials, the plate current begins to rise in a manner deducible from Maxwell's law of distribution of emission velocities for the electrons. For positive potentials, Langmuir has shown that the current curve proceeds to rise in accordance with the three-halves power of the plate voltage. At a definite plate voltage the curve suddenly fails to rise further and remains horizontal for all higher voltages. This behavior is accounted for by the fact that for low voltages only a small fraction of the emitted electrons reach the plate; the remainder, thwarted by negative space charge, return to the filament. Stronger fields, however, overcome the space charges and ultimately cause all the electrons as fast as they are emitted to travel to the plate, after which further increase of voltage can produce no greater effect. Thus saturation is reached precisely as in a vacuum photocell. A higher temperature of the filament will release more electrons per second, and the saturation point will be both advanced and elevated as indicated by the dotted curve.

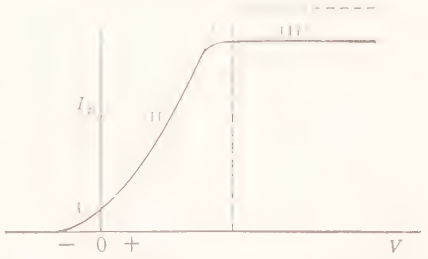

FIG. 41.—Dependence of current on plate voltage in a thermionic tube.

It is of interest to note that complete saturation is apparently never reached with oxide-coated filaments.

Just how the emission of a filament varies with the temperature is expressed in an equation due to Richardson:[71]

$$i = aT^{\frac{1}{2}}e^{-b/T}$$

where a and b are constants, T is the absolute temperature and e is the base of natural logarithms.

It should be clear that, if the polarity is reversed on plate and filament, the electrons must be repelled by the plate and no current can flow. Hence, a thermionic tube can be used as an efficient rectifier for alternating currents.

Thermionic amplifier.—Tubes used as amplifiers contain an additional element, known as a *grid*, which normally surrounds the filament rather closely and is in turn enveloped by the plate. The grid almost invariably is in the form of an open-wound wire cylinder of the same cross-sectional contour as the plate. Due to its proximity to the emitter, an applied potential of one volt may have many times as much influence on emission as the same potential on the plate. The number of volts change required on the plate to produce the same effect on plate current as is caused by one volt change on the grid is defined as the *amplification factor* of the tube, and is conventionally represented by the symbol μ. If the grid is charged negatively with respect to the filament, the grid not only repels electrons from itself but also diminishes or even stops completely the flow to the plate. The curve in Fig. 42 shows the exact manner in which the plate current depends on grid voltage for several values of plate voltage. Because the functioning of the grid as a control of plate current is so sensitive, and the absence of moving mechanical parts obvi-

ates all inertia, and the electrostatic capacity between elements is so small, the three-electrode tube becomes an ideal tool for amplification of weak signals applied to the grid even when the signals fluctuate at extremely high frequencies.

By reference to Fig. 42, it can be seen that if the grid is initially biased to a voltage such that the tube operates at the mid-point of the straight part on one of

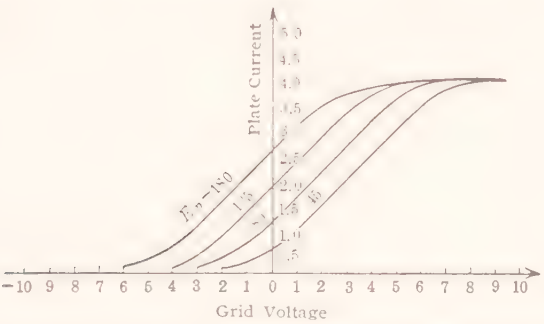

FIG. 42.—Dependence of current on grid voltage in a three-electrode thermionic tube.

the curves, any small change in voltage on the grid will be reproduced very faithfully in magnified proportions by the plate current itself.

Change in the value of the normal plate current is given by the relation,

$$I_p = \frac{\mu E_g}{R_p + R}$$

where E_g is the change in grid voltage from the constant bias, R_p is the effective resistance between plate and filament, and R is the external load resistance.

It should be pointed out that the electrical resistance

between the grid and filament of an amplifying tube may constitute an appreciable part of the leakage resistance R_0 considered above in the photocell circuit. The grid-filament leakage path may exist between lead-in wires over the surface of the glass press within the tube or else between the connections inside the base or between the prongs outside the base. (See Fig. 43.) In case high amplification is necessary, it may become imperative to select tubes having the highest possible

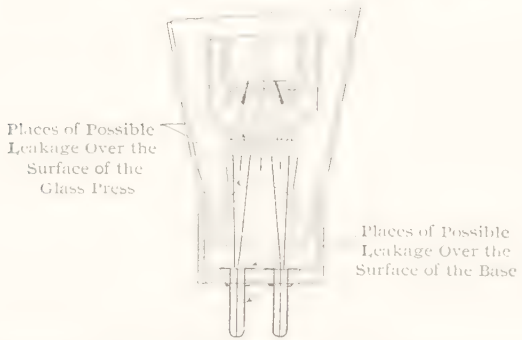

FIG. 43.—Cross-section of a commercial thermionic tube showing most probable leakage paths

grid-filament resistance. Again, because it is impossible to obtain a perfect vacuum, there may occur ionization of residual gases at normal plate voltages. One satisfactory remedy for this difficulty is to operate the tube at voltages below the ionizing potentials of the gases. Surprisingly good results may be obtained with plate potentials of 15 to 20 volts. However, higher efficiency of amplification at low voltages may be obtained by the use of a special four-electrode tube[7] in which the fourth element is introduced for neutralizing space charges.

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CHAPTER IX

THE PROBLEM OF AMPLIFICATION

Having now examined the fundamental features of construction and operation of thermionic tubes, we are prepared to consider schemes for direct-current amplification.

The simple d-c circuit.—One of the simplest direct-current circuits is shown conventionally in Fig. 44. It was suggested by I. Langmuir as early as 1914.[73] The voltage output of the photocell circuit is impressed upon the biased grid of a standard three-electrode tube, which we shall call briefly a *triode*. Fluctuations of light at the cell cause corresponding changes in the grid voltage, which in turn modify the plate current. The modified plate current may be utilized for measuring the intensity or variations in intensity of the exciting light, or simply for operating a relay. In the latter case, the amplification may be made enormous by making the load resistance of the photocell very large. G. duPrell[74] has succeeded in obtaining with a single tube an amplification of many hundred thousand times by taking great precaution against leakage. He coated the outside parts of the tube with paraffin and could use

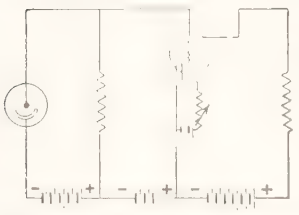

FIG. 44.—A single-stage circuit for direct-current amplification

a load resistance of several hundred megohms. Such high resistance units are difficult to obtain, but can be made by evaporating or sputtering a thin film of metal in a glass tube which has been highly evacuated. Unfortunately these resistors have a rather high negative temperature coefficient.

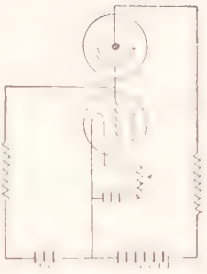

Fig. 45.—A modified circuit for direct-current amplification.

A modification of the single stage d-c unit is seen in Fig. 45. Here the same B battery is used for both photocell and triode, the cathode of the cell being directly connected to the grid, and anode to plate. Although this unit is very compact, it is not capable of reaching the same maximum amplification. The unit can be made still more compact and the capacitance leakage minimized by constructing photocell and amplifier together in one assemblage [75] as shown in Fig. 46. The inner circuit is identical with that of Fig. 45. Satisfactory amplification may be obtained provided the emissive surface remains sufficiently constant.

Fig. 46.—A combined photocell and thermionic tube.

Multistage d-c circuits.—Where still greater amplification is required, we must resort to the use of additional triodes (Fig. 47). Immediately the necessity arises of having a separate voltage supply for the plate of each stage so that the grids may be insulated from one another. These separate supplies

introduce instability on account of their independent variations. As an illustration [76] of a very useful multistage d-c amplifier, we describe the circuit as diagrammed in Fig.

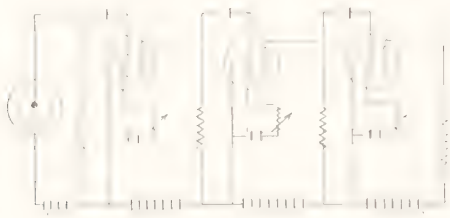

FIG. 47. A multistage circuit for direct-current amplification. Each stage has a separate voltage supply.

48. All the plate potentials are supplied from a common source by means of a potentiometer. There are three tubes, the first two being radio receiving tubes of normal rating, and the third and last being one of higher rating

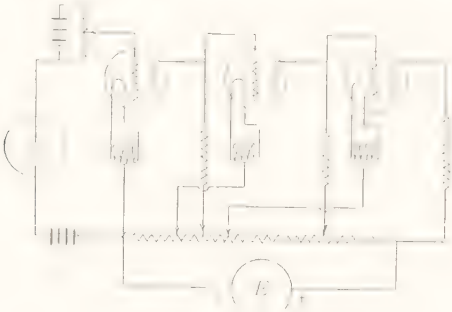

FIG. 48.—A particular circuit for direct-current amplification which has one common power supply.

known as a power tube. The filaments of all the tubes are heated by current from a transformer. The grids of the first and third tubes are biased so as to reduce the plate currents to a minimum, while the grid of the

second tube is biased for a maximum plate current. Thus when the first grid becomes more positive, the plate current through R_1 increases so that the second grid becomes more negative, and in turn the third grid becomes more positive. This particular circuit owes its unusual efficiency to the fact that the changing plate currents cause changes in potential along the potentiometer in such a sense as to aid the grid changes. Hence there is a feeding back of energy which results in *regeneration* of the input signal. In a fashion, the signals build themselves up by superposition of electrical echoes. Great care has to be exercised in the manipulation of the circuit to avoid over-regeneration, which results in sustained oscillations having frequencies determined by the constants of the several sub-circuits. It is this feature of instability which characterizes all multistage d-c amplifiers with great overall amplification.

The a-c circuit. In alternating-current amplifiers the signal is of a pulsating or oscillating character so that the currents dealt with are capable of passing through condensers. This makes possible the introduction of condensers in all the grid circuits to prevent the d-c plate voltages from being impressed directly on the grids. Thus the operation point of the tube in a-c amplifiers is independent of the mean value of the plate current of the preceding tube. Also the same voltage supply can serve for all the plates and great stability for a given amplification is obtained.

Resistance-capacitance coupling. When the input signals consist of a wide range of frequencies such as are encountered in picture transmission or television, it is common practice to use a multistage resistance-coupled amplifier substantially identical with the circuits out-

lined in Fig. 49. The type of coupling is named according to the nature of the load impedance which supplies the signal voltage for the next following grid. Since a pure resistance has no frequency characteristic, the uni-

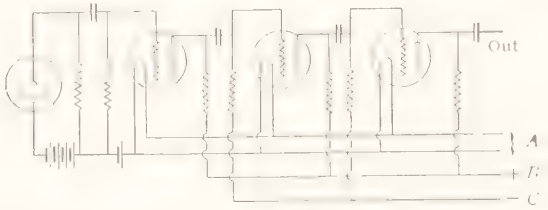

FIG. 49.—A typical multistage resistance-capacitance coupled circuit for a-c amplification.

formity of amplification for signals of different frequencies is distorted at the lower limit only by the increasing reactance of the grid condensers. The *reactance of a condenser* is given by the well-known formula,

$$X_c = \frac{1}{2\pi fC}$$

where C is the capacitance in *farads*. Figure 50 shows graphically how the reactance varies with frequency. At the upper limit, the uniformity of amplification is limited only by the spurious tube and circuit capacities which act as shunts for higher frequencies in the manner already illustrated in Fig. 39. The *fidelity* of a well designed resistance-coupled amplifier,

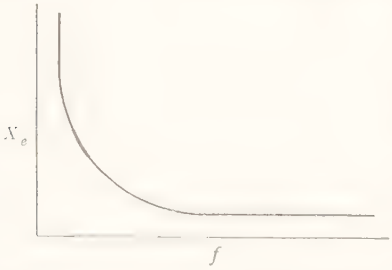

FIG. 50.—The general relation between the reactance of a capacitance and the impressed frequency.

employing the usual type of triode, may be judged from the curve in Fig. 51, which shows a fairly "flat" response between 25 and 50,000 cycles.

The screen-grid tube. To obtain fidelity up to 80,000 cycles, it is convenient to use a special radio tube with electrostatic shielding between grid and plate to prevent capacitance coupling between elements which would result in feed-back to the grid. As in d-c circuits, the regeneration would produce distortion and, what is worse, would cause oscillation. This type of tube is known as a screen-grid tube. A typical struc-

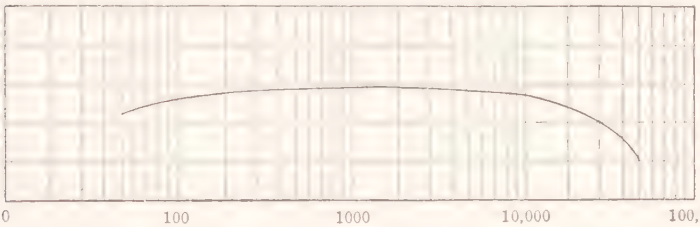

FIG. 51.—A frequency response curve for a well-designed resistance-capacitance coupled amplifier.

ture is indicated in Fig. 52. The fourth element, the shield, almost completely envelops the plate, and itself is charged to a positive potential. As a Faraday cage, it rather effectively prevents induction on the grid due to electrostatic variations in plate potential, while its own positive potential accelerates the electrons controlled in numbers by the grid. The majority of the electrons pass through the meshes of the screen into the field of the plate. In this way normal grid control is preserved together with electrostatic shielding. By employing screen-grid tubes and using precaution to shield externally all grid circuits, flat amplification may be secured up to 80,000 cycles or even higher, if desired.

Of course, the less the amplification required, the flatter the curve can be made.

Inductance coupling. For audio frequency ranges, say from 25 to 10,000 cycles, it is advantageous to use

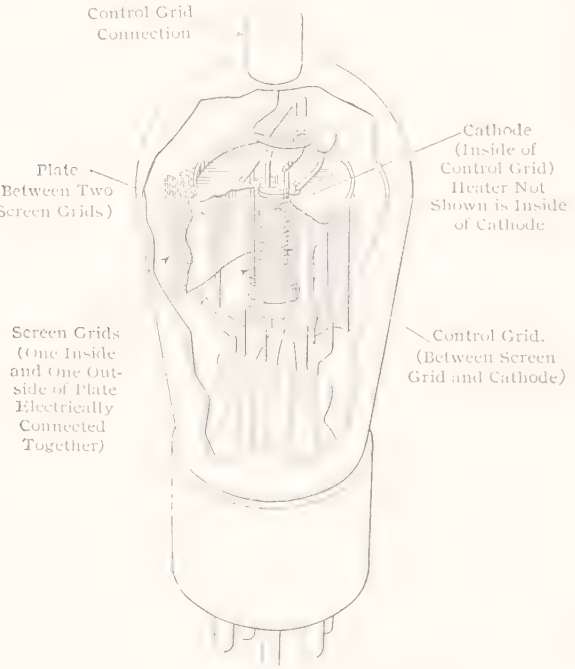
Control Grid Connection
Cathode (Inside of Control Grid) Heater Not Shown is Inside of Cathode
Plate (Between Two Screen Grids)
Screen Grids (One Inside and One Outside of Plate Electrically Connected Together)
Control Grid. (Between Screen Grid and Cathode)

FIG. 52.—The internal structure of a commercial screen-grid thermionic tube.

inductance coupling. Here the load impedance consists ideally of pure inductances, the reactance being computed by the relation,

$$X_L = 2\pi f L,$$

where L is the inductance in *henrys*. Obviously, the reactance is directly proportional to the frequency. For

high frequencies, the impedance becomes so great that the shunting capacitance and leakage are serious factors.

A point of great importance is the fact that maximum voltage output is secured when the output impedance matches the plate resistance of the preceding tube. If the inductance is designed to match the tube for low frequencies, the tendency for the output voltage to rise with frequency will be counteracted by the decreasing efficiency of the circuit due to departure from the optimum condition of *matched impedances.*

The distinct advantage of inductance coupling over resisting coupling lies in the fact that the d-c voltage

FIG. 53.—A circuit with transformer coupling for a-c amplification.

drop across an inductance of a given reactance is much less than the d-c drop across a resistance of the same reactance, and hence a lower voltage supply will produce the same potential on the plate of the tube.

A common form of inductance coupling is the transformer. The reactance of the primary can be made to match the plate resistance of the preceding tube (Fig. 53). Then since the grid to filament resistance of the next tube is very great, the secondary of the transformer may be made of higher reactance than the primary, with the result that a gain of 2 to 6 times may be practically obtained in the transformer itself. Of course the efficiency at high frequencies is limited for the same reasons as given above.

Limitation in amplification. By modifications and combinations of the principles outlined, amplifiers may be built with characteristics almost as desired. But any kind of amplifier has an upper limit of useful gain. The input signals themselves being so weak, any other electrostatic or electromagnetic disturbance may be induced in the initial grid circuit and be amplified along with the desired signals. Also disturbances are introduced within the tubes themselves. Mechanical vibration of the elements produce what are generally called *microphonic noises*. An appreciable part of "tube noise" is due to the *thermal agitation* of electric charges in conductors of the circuit, chiefly in the input resistance.[77] Ultimately, the emission from the filament of discrete electrical particles instead of a continuous electrical fluid constitutes the so-called "*Schroteffekt.*"[78] All such foreign interferences are known as *ground noises* and it is stated that the input signal must have a strength well above the threshold of ground noise if clear undistorted output is to be expected.

Amplification with carrier. Because the design of stable a-c amplifiers of high efficiency and great flexibility has reached a remarkable degree of perfection, it happens that even when the output of the photocell is constant or consists of frequencies including very slow variations, the output is sometimes arbitrarily and artificially superposed upon, or broken up into, a pulsating or oscillating current. This artificial current is called the *carrier* of the signal which modulates its strength. The method is termed amplification with carrier frequency.

Mechanical light-chopper. Perhaps the most obvious means of converting the output of the photocell into

pulsations is by mechanical interruption of the incident light. This may be accomplished by a rotating disk provided with evenly spaced rectangular slots at the periphery as indicated in Fig. 54 (*b*). The disk or "light-chopper," as it is commonly called, is interposed in the optical path at the position of the image of the source, the source being for example a small illuminated spot on a picture.

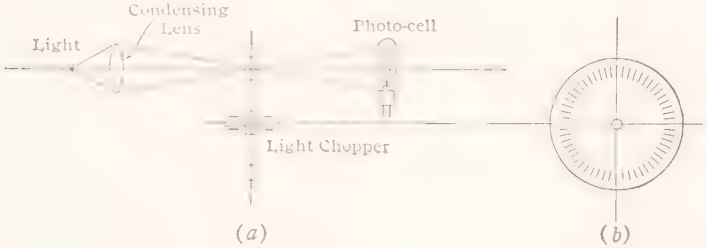

FIG. 54.—(*a*) An optical arrangement for a mechanical light chopper. (*b*) A transverse view of the chopper disk.

If the source should remain constant in intensity, it can be shown that the effective value of the photocell current would be

$$i = \tfrac{1}{4}\sqrt{2}i_0,$$

where i_0 is the peak value attained when the disk is stationary and the beam is not obstructed. Because the incident stream of light is modulated one hundred per cent by the chopper, the amplifier needs to handle only the energy corresponding to the frequencies of the picture.

Unfortunately the irregular wave form of intensity produced by the interruption involves the presence of unwanted harmonics which may prove troublesome. Also any mechanical imperfection of the disk will mod-

ulate the frequency of interruption in a manner detectable in the final output. An improved arrangement is shown in Fig. 55 (*a*) and (*b*). A masking sector with several corresponding slots is fixed adjacent to the rotat-

(*a*) (*b*)

FIG. 55.—An improved optical arrangement for a mechanical light chopper with auxiliary mask.

ing disk. Since the light passes simultaneously through several slots, minor irregularities are averaged out.

Photocell interruptor. A more elegant method involves the use of an auxiliary photocell in series with

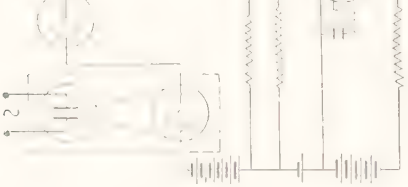

FIG. 56.—A photocell and glow tube unit for introducing a carrier frequency.

the one receiving the signals to be amplified. See Fig. 56. When the auxiliary cell is dark, no current can pass in the circuit. In practice, however, it is illuminated by a neon glow discharge tube whose brightness

varies in proportion to the current passing through it. This exciting current is supplied to the glow tube from an oscillator tuned to the frequency desired for the carrier. If the effective illumination in the auxiliary cell is at least as great as that in the main cell, it is plain that the resultant current will consist of the superposition of the signals and the carrier frequency. This scheme has an additional advantage of being capable of receiving illumination signals from a large area, in which case mechanical interruption would be at least inconvenient.

Kerr cell interruptor. — Another practical method for the artificial introduction of a carrier frequency is optical by nature. Light, being a transverse electromagnetic oscillation in space, generally consists of an infinite number of component frequencies of which the instantaneous direction of electric field is entirely random. When light passes through an optical device known as a *Nicol prism*, all electric oscillations are deflected and absorbed except those components in one particular direction. Light of which the electric vectors are confined to one direction is said to be plane-polarized. Now if plane-polarized light is incident upon a second Nicol prism whose plane of transmission is at right angles to the first prism, it is completely absorbed. However, if the plane of polarization is twisted through an angle, then a definite portion of the light is transmitted by the second prism. It has been found that certain liquids when placed between plane-parallel plates across which a voltage is impressed have the property of effectively rotating the plane of polarization of light. Such a device is known as a *Kerr cell*. In Fig. 57 a Kerr cell is interposed between two Nicol prisms and is excited by an

a-c voltage of the desired frequency. Under proper condition of adjustment,[79] the signals can be faithfully superposed on the carrier. A disadvantage lies in the rather poor optical efficiency.

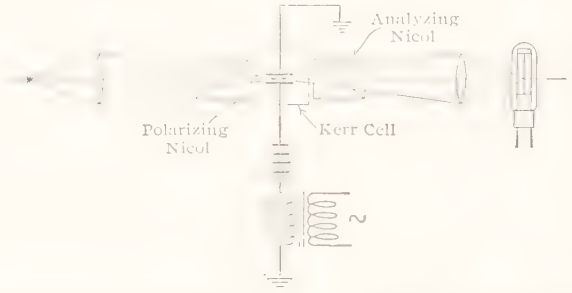

FIG. 57.—Electrical and optical systems for superposing a carrier frequency by means of a Kerr cell.

Methods of mixing with carrier. We wish to make reference to a scheme[80] by which the carrier frequency is introduced by transformer coupling directly from an oscillator as illustrated in Fig. 58. By this method the

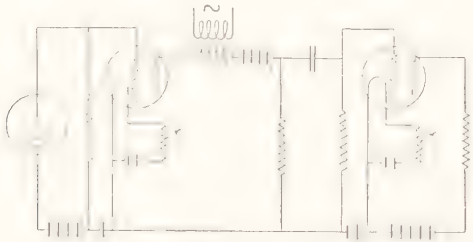

FIG. 58.—A circuit for introducing a carrier frequency by transformer coupling.

signals and carrier are mixed in the plate circuit of the first tube. However, it is difficult to secure a high percentage modulation of the carrier, and the stability of the circuit is not altogether satisfactory.

It will be recalled from Chapter I that Elster and Geitel first obtained an indication of the character of photo-electric carriers by observing a modulation of the current by an applied magnetic field. Exactly this method may be employed for introducing a carrier frequency. A coil is placed down over the cell and an a-c exciting current is supplied from an auxiliary oscillator.

Radio-frequency amplification. – Promise of improvement in amplification is given by recent developments which involve the use of radio frequencies. Empirical results obtained with familiar types of radio broadcast receivers have shown that a considerable amount of ground noise can be eliminated, even for great overall gain, by employing amplification of radio rather than audio frequencies. The chief reason is that audio noises do not pass through radio frequency circuits unless they are introduced as modulators of the carrier. Thus a new field is opened up for building up weak photocell signals. The difficult problem arises at once of introducing a high-frequency carrier into the photocell circuit. Obviously most of the methods outlined above are not suitable for frequencies above, say, 100,000 cycles. The mechanical chopper and the glow tube are out of the question. The Kerr cell offers too much complication. The only reasonable method seems to be the direct induction of high frequencies in the cell by magnetic modulation or the direct impression of high-frequency potentials upon a control grid within the cell. However, the high effective resistance of the cell and its finite inter-electrode capacitance present themselves as obstacles. The logical solution is the same as that arrived at in the screen-grid radio tube, namely,

the shielding of the anode from the control grid. A *screened-anode photocell* developed in Westinghouse Research Laboratories is shown in Fig. 59. The anode and cathode may have structures similar to those in normal cells, but one grid closely surrounds the central anode wire, while a second grid is situated between the first grid and the cathode. The cell is highly evacuated. The carrier frequency from an oscillator is impressed between anode and control grid and is modulated by the photocurrent existing instantaneously between anode and cathode. The circuit is illustrated in Fig. 60. The method shows promising results in the field of television.

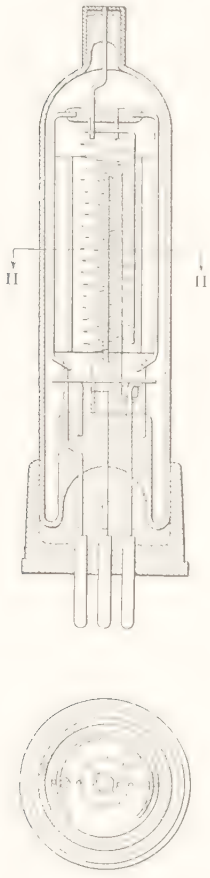

FIG. 59.—Views of a screened-anode photocell with control grid

Self-oscillating cells.—Again, it is possible to cause a four-electrode photocell to create its own oscillations. This can be done by introducing the cell in the circuit shown in Fig. 61. It will be observed that the shielding grid functions as the main anode, whereas the usual anode serves as a secondary electrode. A *dynatronic* characteristic is secured similar to that described by A. W. Hull[8] for a thermionic tube.

Oscillations can also be produced in a gas-filled, two-electrode cell by operating at the glow point or on an unstable part of its characteristic.[9]

The frequencies, however, are of the audible range and the sensitive surface must be of a character not injured

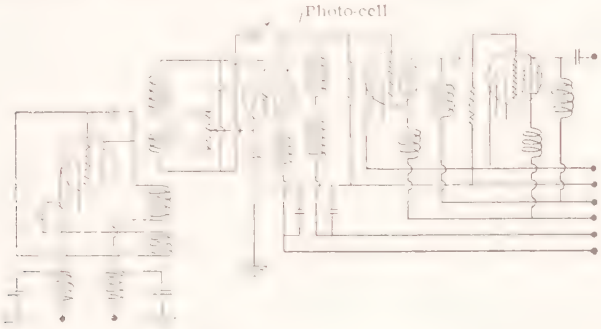

FIG. 60.—A circuit employing a screened-anode photocell in radio frequency amplication of the light signals.

by positive ion bombardment. The circuit employed [83] to secure such oscillation is given in Fig. 62.

Gas-discharge tubes. Beside the radio tube type of amplifier, we wish also to consider the type involving

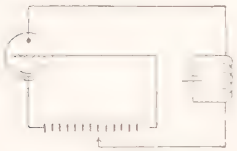

FIG. 61.—A circuit in which a photocell becomes self-oscillating.

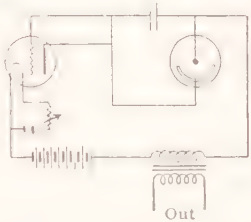

FIG. 62.—An oscillating circuit which employs a gas-filled two-electrode photocell.

the use of a controllable glow-discharge tube. Although not suitable for linear amplification, the glow tube is admirably adapted to the operation of relay devices.

The *grid-glow tube* described by D. Knowles [84] and illustrated in Fig. 63 is a neon-filled bulb containing a

large metallic cylinder for cathode and, centrally located, two shaped wire pieces for anode and control grid. The anode area exposed is quite small and the grid wire is so constructed as to provide an effective electrostatic guard for the anode. If a potential of several hundred volts is applied between anode and cathode, while the grid remains unconnected, the latter will immediately accumulate a negative charge strong enough to prevent a discharge through the gas; but if the grid charge is removed, the gas breaks down at once, and a current, limited only by the circuit resistance, flows through the tube. Because the capacity of the grid is exceedingly small, the control is supersensitive. Under favorable conditions, the amplifying power may reach the order of several million times. If the supply voltage is d-c, the discharge cont nues to flow even when the grid is again free, but with a-c voltage the discharge is interrupted each time the potential passes through zero. Thus it is possible to obtain with a-c supply both on and off operation of the relay.

Fig. 63.—A grid-glow tube.

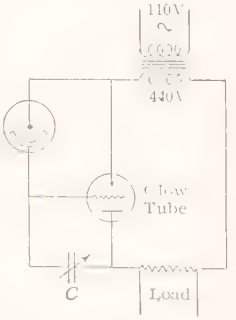

Fig. 64.—A circuit for a photocell and grid-glow tube unit.

In combination with a photocell, the glow tube may be connected as shown in Fig. 64.

The photo cell is connected directly between anode and grid. A variable condenser between grid and cathode of the tube provides a practical adjustment of sensitivity and stability. Due to the high voltages involved, the photocell must be highly evacuated to prevent a continuous glow discharge between its own terminals. A current of the order of 0.1 microampere through the

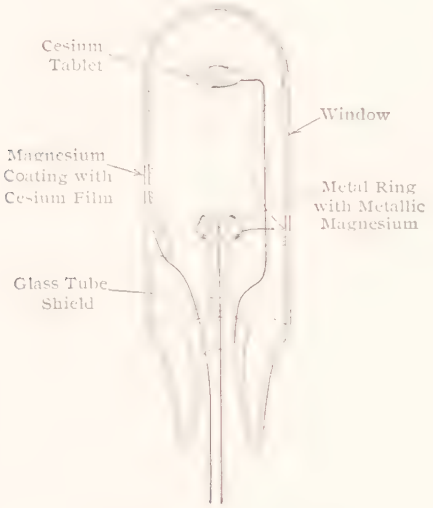

FIG. 65.—A photo-glow tube.

photocell is sufficient to initiate a current of about 50 milliamperes in the glow tube.

Much greater power can be secured by the use of a *glow tube provided with a hot filament* for cathode.[85] Such tubes are still sensitive enough to be operated by photocell currents, and control may be had of discharge currents amounting to several amperes.

The so-called *photo-glow tube* is a convenient relay device for certain applications. It is essentially a combination of photocell and grid-glow tube in one glass bulb. (See Fig. 65.) The photo-emissive surface is formed directly on the glass wall, an evaporated coating of magnesium serving for electrical contact. The coating is in turn electrically connected to the controlling element of the tube. The bulb is filled with an atmosphere of an inert gas such as argon. When light shines into the tube, the sensitive surface and control element become positive, permitting an ionizing discharge to occur through the gas.

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CHAPTER X

THE PHOTOCELL IN SOUND MOVIES

Without a doubt, from a commercial point of view, the most important application of the photocell is to the art of producing audible motion pictures, commonly spoken of as "*talking movies.*" Beginning only a few years ago, this new industry has already taken gigantic strides to replace the silent screen. The photocell, formerly an insensitive laboratory device for photometric measurements, has been swept along in the rapid development as one of the indispensable organisms of sound projection assemblies, and is now a common article of factory production. When one considers that in the United States alone there are more than 23,000 moving picture theaters, practically all of which will soon be converted into sound-picture auditoriums, and then thinks of the potential possibility of the demand for hundreds of thousands of sound projectors in the home, one can understand what an impetus photocell development has received.

At the present time, great success has been attained by a scheme of projection in which the sound effects are picked up electrically from a phonograph record started and maintained in synchronism with the picture sequence. The synchronizing, being manual, requires the attention of a skilled operator and may at times be somewhat faulty. Automatic synchronization of sound

and picture is obtained when both visual and audible effects are simultaneously recorded on the same film. A photo-electric device is necessarily involved in the reproduction of sound from a photographic film.

Sound recording on films. Although the industry is recent, the idea of sound recording on films is quite old. As early as 1886 C. E. Fritts[86] outlined a scheme for photographing audible effects directly on a film, but since the necessary devices were not available for practical accomplishment, the idea did not receive recognition at the time. Ernst Ruhmer in Germany actually succeeded in recording by means of the "speaking carbon arc" in 1901. Three years later, in 1904, E. Gehricke, also of Germany, published an article on the use of a glow-discharge tube for the same purpose. Gradually the art of recording developed through the contributions of many investigators until the present highly perfected methods were evolved.

Modulation of light by sound is secured nowadays by the use either of a glow-discharge tube, or of a Kerr cell, or of a vibrating mirror or shutter. All of these modulating devices may be arranged to produce one or the other of two types of sound track on the film: *(a) variable density,* or *(b) variable area.* In the first type, a track of uniform width varies in opacity along the length of the film. In the second type the record is of uniform opacity but varies in width on the track. Figure 66 is a photograph of some portions of film showing clearly the different appearance of the tracks.

Reproduction of sound. Fortunately both schemes involve the use of identical optical systems and the same scheme of photoelectric reproduction will serve equally well with either kind of film. Essentially, light

from a narrow, horizontal illuminated slit is focused into a fine line across the track. Whether the optical density

FIG. 66.—Portions of film illustrating sound track of the variable density (left and center) and variable area (right) types.

changes as the film moves or whether the width of the record changes, the amount of light transmitted by the film varies in exact accordance with the original sound

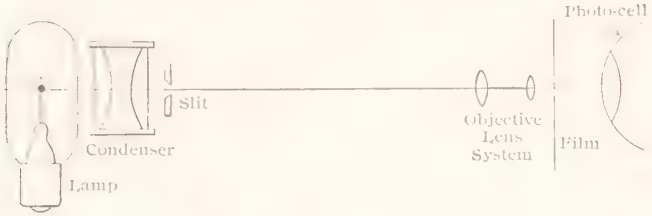

FIG. 67.—A practical optical system for reproduction of sound from film.

and produces corresponding currents in the photocell receiving the light.

Figure 67 illustrates a practical optical system for

the purpose.[5] The source is a heavy tungsten filament wound closely in a horizontal helix. Operating at about 3000° C., the filament not only has a reasonably long life for its great intrinsic brightness, but also has a sufficiently large heat capacity so that fluctuations of temperature due to ripples in a rectified and filtered current supply are not serious enough to affect appreciably the photocell output. It is an important prerequisite that the luminous flux from the source must be constant, especially when the amplifier is highly corrected for low frequencies, in which case it may be imperative to use storage batteries as filament supply. It is also very important that the film shall move under the beam with constant speed. This requirement is not easy to fulfill due to the vibrations introduced by the general movement of the projector and by the sprocket teeth. Quite elaborate precautions are used in modern projectors, such as mechanical filters, curved gates, etc., in order to secure uniformity of speed.

An efficient compound condensing lens forms an intense rectangle of light upon a narrow horizontal slit. The illuminated area must be greater than that of the slit so that microphonic movements will not cause any variation in the flux through the slit. Although very narrow, the slit is wide enough not to produce diffraction. The wedge of main intensity is received by a second condensing system which focuses upon the sound track a reduced image of the slit. Finally the light, modulated by the film, enters a photocell. Mechanical adjustments may be made for perfect alignment of the optical system so that the rectangular strip of light on the track exactly coincides with the elementary areas of the recorded sound.

Frequency restrictions. The rectangle of light must be long enough to cover the width of the track and have a narrow dimension whose largest permissible size is determined for a given rate of film travel by the value of the highest audible frequency that is to be reproduced in order to obtain good quality of sound.[88] Assuming that it is essential to reproduce frequencies as high as 5000 cycles per second and the speed of the film as 18 inches per second, the length of the shortest wave on the track is 0.0036 inch. If such short modulations are to appear in the photocell current, it is clear that the slit image dare not be wider than a small fraction of this shortest wave record. In practice the width is reduced to 0.001 inch as a fair compromise between fidelity and intensity.

Because of this optical definition of light, the actual luminous flux into the cell is so small as to deliver a power of only about 0.01 microwatt. Since it requires about 20 watts to operate the loud speakers in a medium sized theater, it may be seen that an amplification of two billion times is necessary; and this overall amplification should be linear over a range of frequencies from about 60 to 8000 cycles.

This range can be effectively handled by transformer coupling, which is therefore employed in most commercial installations.

Mechanical features. The construction of a sound attachment, or *sound "head"* for a modern movie projector is shown in Fig. 68. The photocell is housed within the sound head and faces close to the film. Its necessary location presents a difficult problem of securing satisfactory coupling to the amplifier. If connections are made by a cable or cables, enough capacitance may

be introduced to cause appreciable attenuation of high frequencies, as was explained in Chapter VIII. One

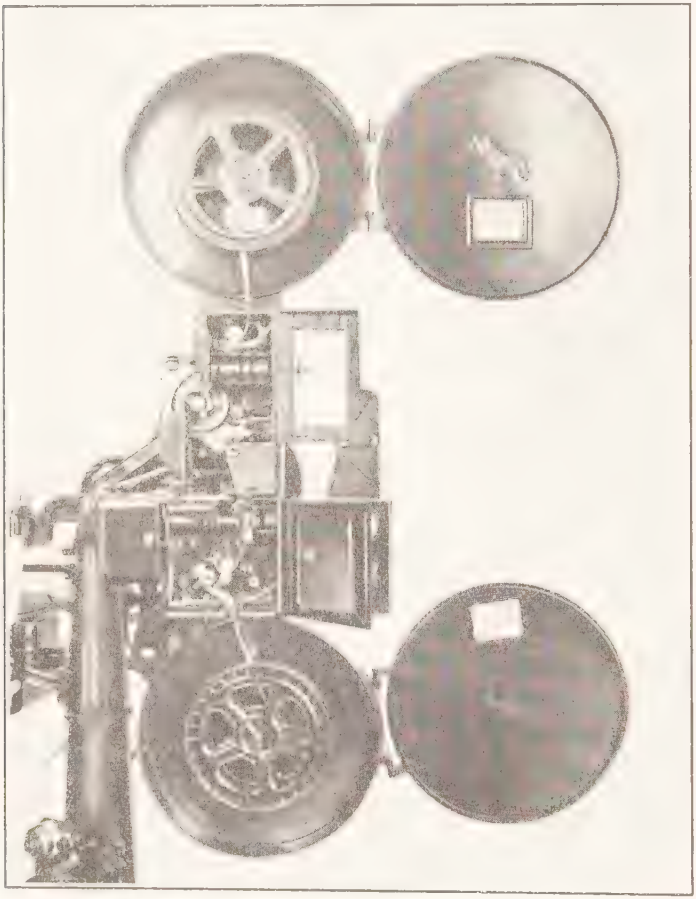

FIG. 68.—A sound head for a modern projection instrument.

solution is obtained by mounting the first stage of the amplifier within the sound head and close to the cell.

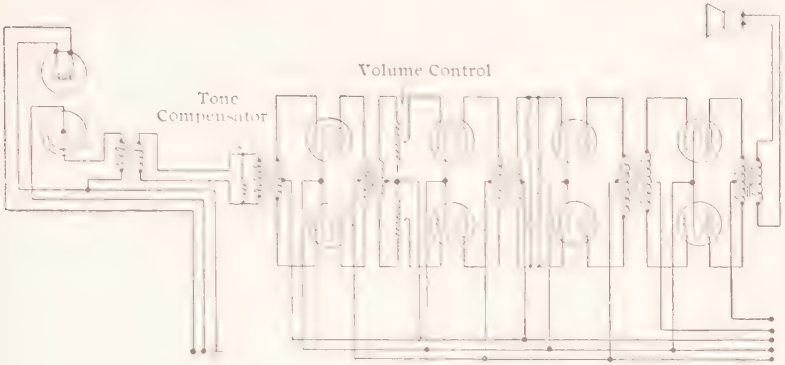

FIG. 69.—The circuit diagram for a Photophone amplifier.

The new trouble of microphonic distortion produced by vibration of rapidly moving mechanical parts can be minimized by using triodes of especially rigid construction and by mounting cell and tube on elastic supports.

An alternative scheme is to step down the photocell voltage output by a transformer, transmit the low voltage signals through a shielded cable to the amplifier where they are stepped up by a second transformer and applied to the grid of the first stage. It is thus possible to design the transformer so that the impedance of the cable may be matched

FIG. 70.—The panel of a Photophone amplifier.

to that of the photocell and the effect of capacitance is minimized. This principle is employed in the Photophone amplifier for commercial 35-mm. films. A circuit diagram is given in Fig. 69.

The actual appearance of the panel of a Photophone amplifier is shown in Fig. 70.

Amplifiers for sound movies. - Amplifiers designed for use in theaters must be flexible enough to cover the needs of any individual installation and must be decid-

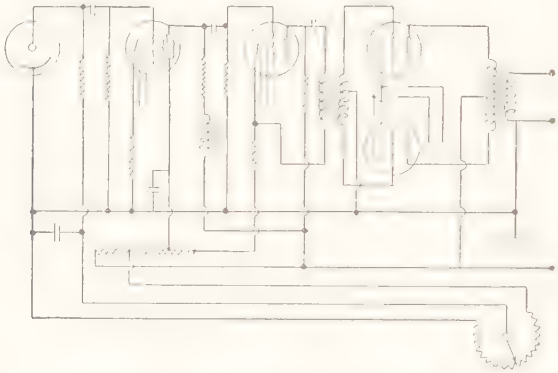

FIG. 71.—A circuit designed for the amplifier of a home sound projector.

edly fool-proof. Hence they are built with a large safety factor of power deliverance and with definite controls. They are essentially bulky in dimensions. In sound projectors for home use, the problems are distinctly different. Although the power requirement is less, the restriction in space is even more so. Because the home projector uses 16-mm. film instead of the 35-mm. film standard for theaters, the wavelengths of frequencies recorded on the sound track are condensed somewhat in the same proportion. It may be computed that for the same fidelity as defined for the larger film,

the home projector requires a slit image only about 0.00025 inch wide. Thus the amount of available light for the cell is unbelievably small. Also the difficulty of sound recording for high frequencies is proportionately increased.

To meet these difficulties, a circuit of the type outlined in Fig. 71 may be used. It employs a screen-grid tube and only two other stages, but sufficient power is

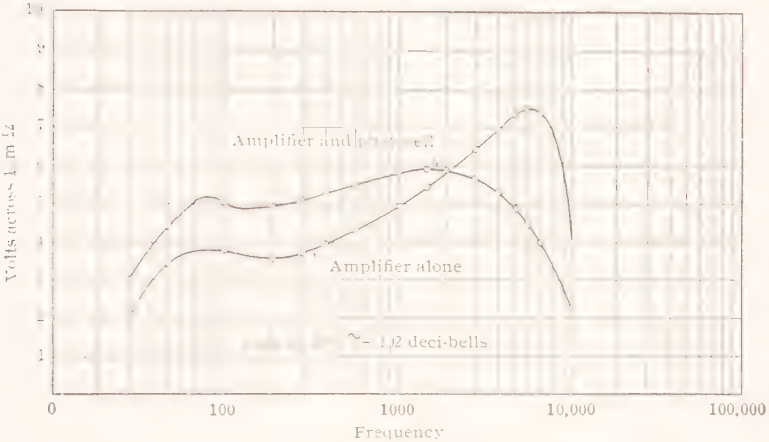

FIG. 72.—Frequency response curves of the circuit in Fig. 71. (By courtesy of A. Shoup.)

gained to operate a dynamic speaker at full volume. To avoid capacitance shunting, the cell is mounted with its base closely adjacent to the grid lead of the first stage. Furthermore, to neutralize all other sources of high frequency attenuation such as inherent inertia of gas cells and lack of definition on sound tracks, the amplifier is peaked at the high frequency end, as indicated in Fig. 72, where curves are given for frequency response of the amplifier alone and for overall amplification from cell to speaker.

The physical dimensions of the amplifier and its power supply can be judged from Fig. 73.

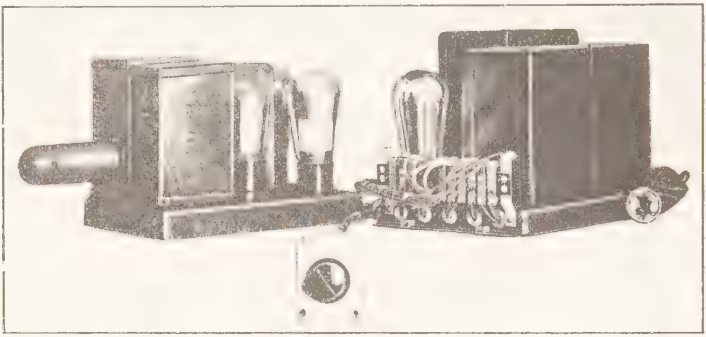

FIG. 73.—The finished amplifier constructed according to the circuit of Fig. 71.

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CHAPTER XI

THE PHOTOCELL IN FACSIMILE TRANSMISSION

Work on electrical transmission of pictures was begun long before photocells were known. The first significant experiments were performed by A. Bain and F. Bakewell in 1843 and 1848, respectively. Both used for purposes of transmission a specially prepared picture consisting of conducting and insulating portions and provided means of exploring by an electric contact. Even this crude scheme was perfected to such an extent by Caselli that during the decade of the sixties it was exploited for a while commercially for transmission over wires between Paris and Lyons in France.

The electric contact method was ultimately replaced by a scanning system in which a translucent replica of the original picture was explored by a pencil of light. A selenium cell served to transform variations in optical density into corresponding fluctuations of current. This scheme was sufficiently practical to induce A. Korn in 1907 to attempt commercial transmission of manuscripts and pictures over telegraph wires (Fig. 74). However, it was not until the introduction of the photocell that results were obtained comparable to those secured by present-day devices.

Methods of scanning.—There are now two principal methods of scanning. The first method, similar to that of Korn, requires the preparation of a diaphanous replica

of the subject to be transmitted. This diapositive is wrapped about a translucent cylinder upon whose surface is focused a small spot of light. The light which penetrates the positive is incident upon a photocell. By rotating the cylinder and simultaneously advancing it along its axis, the whole surface is gradually explored. The photocell faithfully responds to every minute change in translucency. It is evident that the mean value of luminous flux in the cell can be made relatively

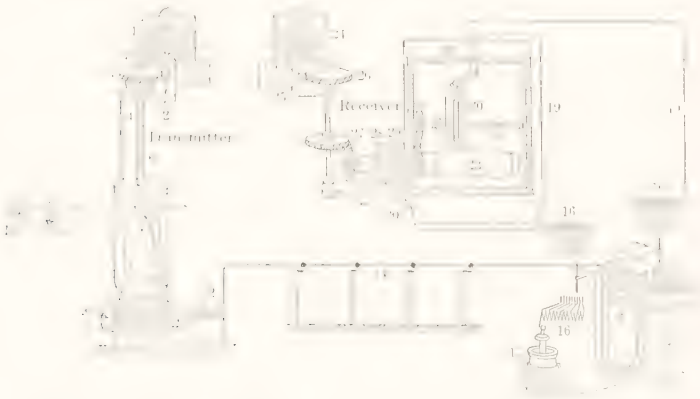

FIG. 74.—Korn's system for sending pictures over telegraph wires.

great and hence no difficulty is encountered in amplification. A highly developed commercial installation by the Bell Telephone Company [8] employs this principle for transmission over telephone lines.

Since it is very objectionable in a modern transmitter to necessitate preparation of diapositives, a method of direct scanning of the original has been developed. By this method only light which has been scattered from the surface reaches the cell and its output is consequently greatly reduced. This implies that the effi-

ciency of the optical system becomes very important. A number of optical arrangements have been introduced. In general they may be divided into two classes.

In the first class,[90] the original is illuminated by a more or less concentrated spot of light. From this relatively large illuminated area, a spot of desired dimension is selected optically by projecting an image of the area upon a perforated diaphragm. A photocell situated back of the diaphragm, shown in Fig. 75, receives

FIG. 75.—One type of optical system used in facsimile transmission.

light only from the portion of the original which is imaged over the orifice in the diaphragm.

In the second class of optical arrangements, the size of the scanning spot is initially defined and then projected onto the original. As much as possible of the scattered light is then gathered into a photocell.

An illustrative diagram[91] of the second class is given in Fig. 76. The image of an incandescent filament is focused upon a diaphragm D. A tiny circular orifice in the diaphragm serves as a secondary source, a sharply defined image of it being formed by the lens L upon the picture wrapped about the cylinder. Surrounding L is a parabolic reflector whose focus coincides with the luminous spot. Light scattered from the original is

gathered by the reflector into a fairly homogeneous parallel beam which is deflected into the photocell by means of the plane mirror *M*. This optical system with an ordinary automobile headlamp as a source is capable of producing a current of about 0.05 microampere in a high-vacuum photocell. An amplifier of three stages, using two screen-grid tubes is sufficient to deliver power for the operation either of a receiving apparatus or of the modulator of a broadcasting station.

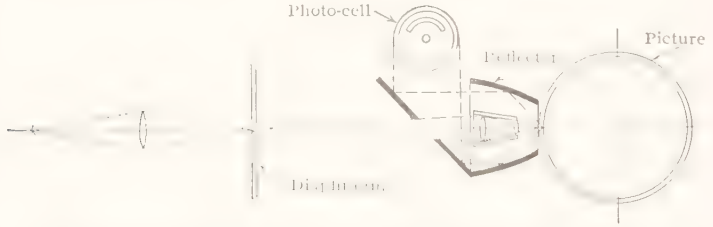

FIG. 76.—A second type of optical system for facsimile transmission.

Types of transmitters. The transmitter shown in Fig. 77 is of an *intermittent* type. In order to transmit a new picture, the machine must be stopped and the cylinder reloaded. Inconvenience of delay has been obviated in the *continuous* machine pictured in Fig. 78. In both machines the optical system, photocell circuit and amplifier are identical.

Receiving systems. For the reception and recording of facsimile signals sent out from the original, numerous methods have been evolved and developed to a certain degree of practicability.

Bakewell and Caselli both used a special paper impregnated with an *electrolytic* solution which changed in color when a current passed through it. The deepness of the resultant color depended on the intensity of

the current and hence a current modulated by the facsimile signals would give a reproduction of the original provided the two systems were kept in synchronism.

A method of recording introduced by Mayer and used to some extent at present is *electro-mechanical* in

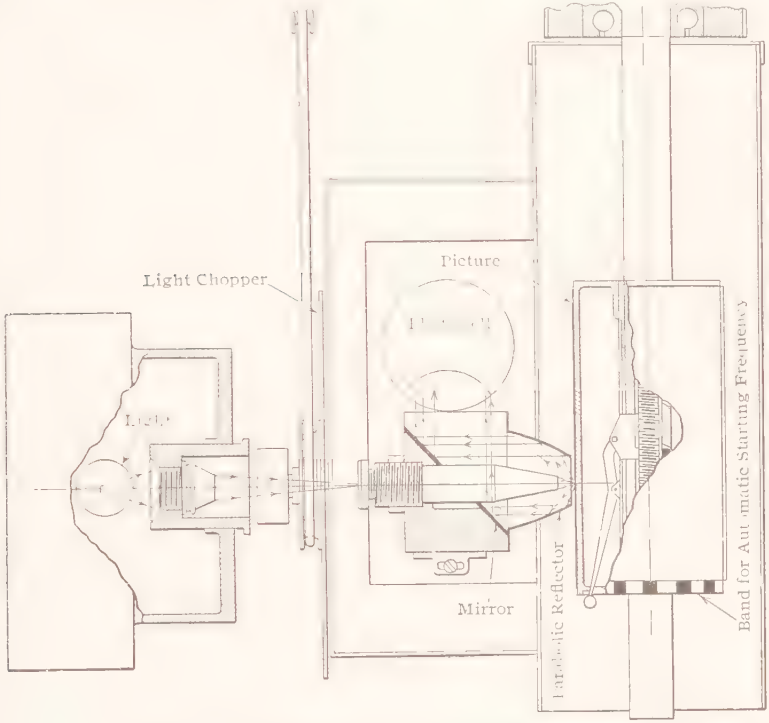

FIG. 77.—A picture transmitter of the intermittent type.

character. A small electromagnet operated by signal impulses is connected with a tiny hammer which strikes a carbon sheet secured to a white under-sheet. Each stroke leaves an imprint the size and shade of which are determined by the force of the blow.

The method most widely used at present is a *photographic* one first introduced by G. Little in 1867. The receiving system consists essentially of a source of light modulated by the transmitter signals and focused as a small spot on a moving photographic film. Modulation may be effected through the agency of an electromagnetic shutter, a Kerr cell or a glow tube. The photo-

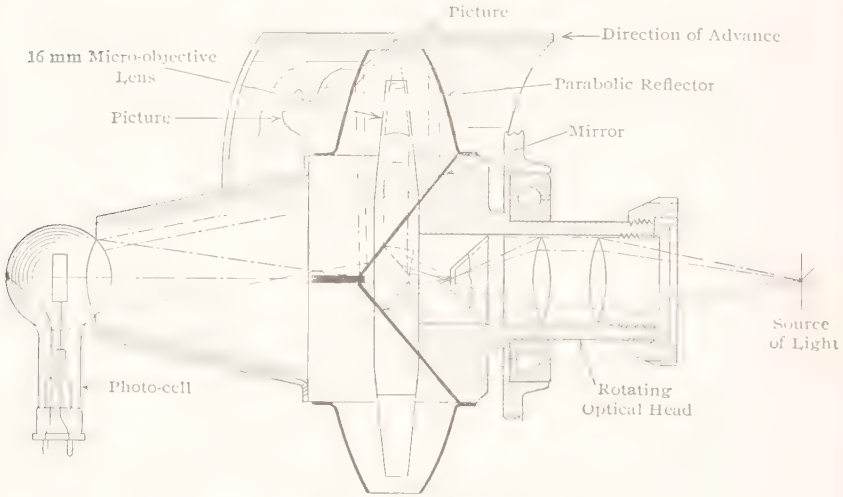

FIG. 78. A picture transmitter of the continuous type.

graphic method presents the advantages of giving either a positive or a negative picture and of producing a more artistic result. The only marked disadvantage is the requirement of time for the development, fixing, washing and drying of the film.

Synchronizing. For correct reception, the receiving machine must always be kept operating at precisely the same speed as the transmitter. Experience indicates that perhaps the simplest and most reliable means for

obtaining synchronism of transmitter and receiver is to control the speed of each separately by two independent tuning forks of precisely the same natural frequencies. The best forks are made of a special alloy which has a low temperature coefficient of expansion and are operated at a fixed temperature. The regulation is sufficiently accurate to give very satisfactory reproductions.

Amplifiers for picture transmitters. Amplification of picture signals presents its own peculiar problem. The scanning of the picture proceeds usually at a relatively slow speed. If a 5×7-inch picture is transmitted in 4 minutes with a definition of 100 lines per inch—an average rate of transmission—the speed of scanning is about 0.5 second per line. For portions of pictures where the surface is of a uniform tone—either black, white or half-tone—the response of the photocell will of course be a constant direct current. Since, as was shown in Chapter IX, direct-current amplification is not desirable, some provision must be made for converting such monotonous signals into related impulses. This can be done very conveniently by the carrier frequency method of amplification. By this means a given uniform scanning path is actually broken into a large number of small dots sufficiently fine and contiguous to appear on the reproduction as a continuous image of the original. Either a mechanical light chopper or any other scheme, as previously described, may be employed to produce the carrier frequency.

The carrier method involves an interesting requirement of the amplifier, due to the peculiar wave band produced. Continuing our illustration of scanning, if we consider the resolution along a scanning path to be the same as at right angles to the path, each path or

line may be regarded as composed of 100×7 or 700 elements, all of which are scanned in 0.5 second. Since the highest possible frequency will be encountered when contiguous elements alternate in tone, a pair of elements constituting a cycle, the maximum picture frequency will be $700/2 \times 0.5 = 700$ cycles per second. It is usual practice to have the carrier frequency at least twice that of the maximum scanning frequency. Assuming a value of 2000 cycles for the carrier, the width of the entire frequency band will be 2000 ± 700 or between 1300 cycles and 2700 cycles. This range

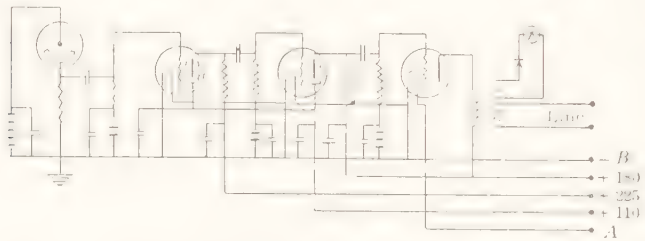

FIG. 79.—A circuit suitable for an amplifier in facsimile transmission.

permits the use of reactance coupling tuned broadly to the frequency of the carrier. An appropriate circuit is presented in Fig. 79.

Of course, a transformer-coupled amplifier similar to the one illustrated in connection with sound movies can also be employed for picture transmission.

For practical reasons, it is often desirable to have the transmitting machine separate from its associated broadcasting station. Sometimes the distance of separation may amount to several miles, as for example, when the station is outside a large city and the machine is located in a business district of the city. In such case, the two systems must be connected by wire lines which

should be corrected to the frequency band corresponding to the speed of the machine.

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CHAPTER XII

THE PHOTOCELL IN TELEVISION

We have stated in effect that both sound movies and facsimile transmission received a great impetus with the advent of the photocell. The statement is even more applicable to television, for television of a quality good enough to deserve the name is absolutely impossible without the photocell.

In a sense, television is simply an enormously accelerated picture transmission, a series of almost instantaneous views of a moving object being so rapidly presented in succession that the eye is deceived due to *persistence of vision*, and continuous movements appear to be reproduced. The physiological aspects are precisely the same as in the art of moving picture projection. However, the speed with which each view of the object is presented necessitates the solution of entirely new problems in respect to method of scanning, system of optics and process of amplification. The result is that television apparatus as a whole bears little resemblance to that of its more sluggish precursors.

Problem of scanning. If a picture to be "*televised*" should contain the same number of picture elements as are used in facsimile transmission and the scanning should be completed in about 1/16 second, then the picture frequencies would be impossibly high. Fortunately, practice has shown that the reproduction of a

moving object may be made with fewer scanning lines than that of a still object for the same final quality. Fair definition may be obtained with only 48 lines for a picture 5×6 inches, while a still picture of the same size would require roughly ten times as many lines. One hundred lines would produce an excellent television picture. If we assume, for illustration, 80 lines per picture, and assume also that there is equal vertical and horizontal definition for pictures whose edges are in the ratio of 4 to 5, the maximum picture frequency will be:

$$n = 80 \times 100 \times 16\ 2 = 64{,}000 \text{ cycles}$$

This means that a given transmitting carrier frequency will be modulated plus and minus 64,000 cycles if both sides of the band are used. The band width is therefore 128,000 cycles, or more than 12 times that at present permitted for broadcasting of music and speech. Certainly the width is the maximum that can be contemplated at this time.

The Nipkow disk. The rapid scanning in itself presents a difficult problem. Of all the methods proposed for the purpose, the most common, and perhaps the simplest, is the so-called Nipkow disk invented by P. Nipkow[92] in 1884. The disk is provided with a single spiral of holes as shown in Fig. 80. Originally an optical image of the object to be transmitted was formed upon the disk within the two concentric circles bounding the spiral. The radial distance between the first and last hole determined the maximum height of the image, while the circular distance between successive holes corresponded to the width of the image. A photosensitive element was placed back of the disk just opposite the image. In the Nipkow patent description, a

set of thermocouples was suggested as one possibility for the sensitive element!

When the disk is rotated, each hole describes a path under the image once per revolution. Just as any one hole finishes its path, the next succeeding one begins one space below. Thus at a given instant light from only one spot of the image affects the sensitive element and produces an electric effect proportional to the intensity of that spot. In one complete revolution the entire

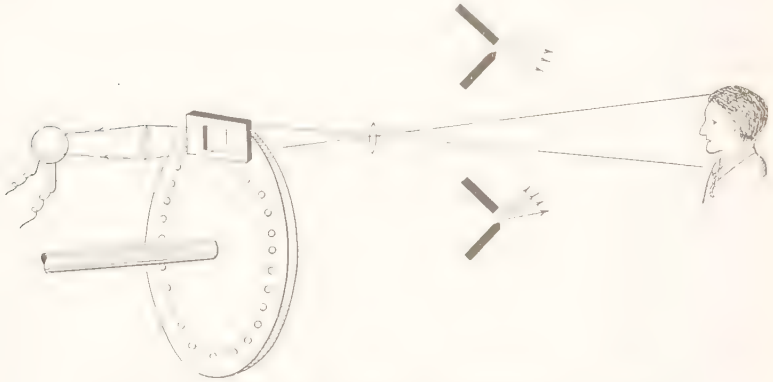

Fig. 80.—The Nipkow disk as used in one method of scanning.

image has been converted successively into a definite series of electric impulses.

When one considers the faintness of illumination produced by an optical image of a non-luminous object and then figures that on the average (for an 80-line picture) only 1/6400 of the total flux enters the photosensitive device at one instant, and that each element affects the sentitive device only 1/102,400 second when it is represented at all, it becomes evident that even with the modern photocell the problem is almost hopeless.

Ekström's inverted system. As a way out of the difficulty, it was proposed by A. Ekström [93] in 1910 to reverse the system of optics. Instead of dividing an optical image into numerous elements, he suggested scanning the object directly by means of a moving spot of light and receiving the light reflected from the spot by a photocell placed very close to the object. There are two distinct advantages gained. First, the spot of light may be made very intense by concentrating the radiation from a brilliant arc. Second, a large amount of light may be collected by employing either a very large photocell or else a large reflector with a small photocell.

The combination of the Nipkow disk with the Ekström scheme of optics made possible the first practical solution * of the television problem and is used extensively even at the present time.

The substitution of lenses for plain holes in the disk and other important optical advances permitted the first approach even to direct television without the intermediate process of scanning with a moving beam."[4]

Amplifiers for television.—It appears quite obvious that with the relatively small amount of light available in the photocell at one time and with the very high frequencies involved, all the precautions outlined for other applications become here of supreme importance.

The photocell is connected to the first stage of the amplifier either by a short low-capacitance cable or else

* C. F. Jenkins, Washington, U.S.A., made his first laboratory demonstration of "radio vision" on June 14, 1923. (See his book Vision by Radio, Radio Photographs, p. 119, 1925.)

J. L. Baird of London, England, gave a public demonstration of his "Televisor," Jan. 27, 1926. (See Television, by Alfred Dinsdale, Isaac Pitman & Sons, publishers, p. 49, 1926.)

The Bell Telephone Laboratories exhibited their system of television in April, 1927. (See B. S. T. J., Vol. 6, Oct., 1927.)

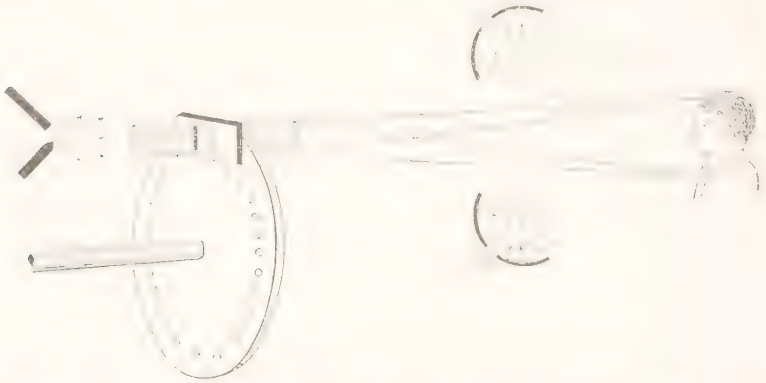

FIG. 81.—An assembled view of a complete amplifier unit for photocell units in parallel.

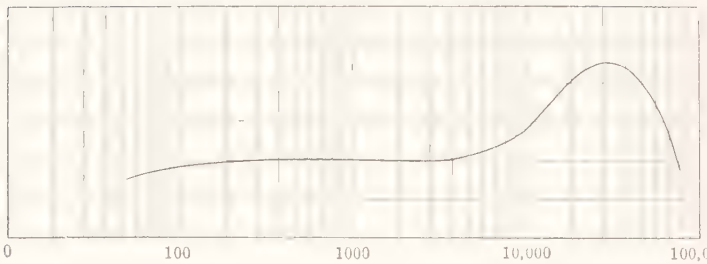

FIG. 82.—The frequency response curve of an actual amplifier showing peak at 30,000 cycles. (By courtesy of K. West.)

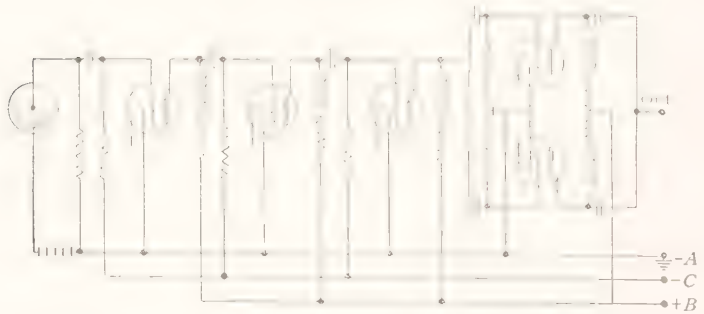

FIG. 83.—The circuit employed to obtain the frequency response shown in Fig. 83.

the first stage is situated in close proximity to the cell. Sometimes several photocell units connected in parallel are arranged about the explored object. See Fig. 81.

The lowest possible frequency encountered in television must be that of the number of pictures transmitted per second—say 16. Hence the frequency range extends from about 16 to 60,000 cycles. No very low frequencies or d-c components are present as in facsimile transmission. Hence it is not necessary to introduce an artificial carrier frequency in order to amplify by a-c methods. However, it is no easy task to design an amplifier which will give overall a linear gain for the entire spectrum of frequencies. Because there are inevitable high-frequency losses in the photocell circuit, it is customary to peak the amplifier curve, as indicated in Fig. 82. The peaking may be done by inserting suitable reactance in the plate circuit, as shown in Fig. 83. The actual appearance of an amplifier built according to this wiring diagram may be seen in Fig. 84.

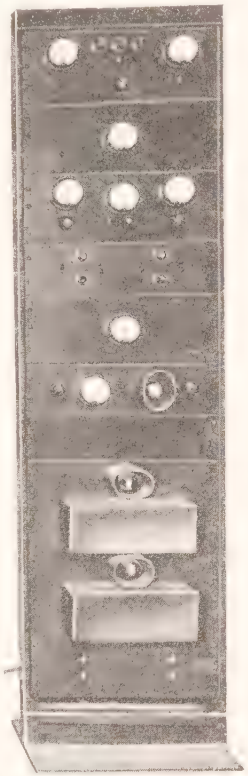

Fig. 84.—The appearance of a television amplifier with the circuit of Fig. 83.

The same result may be obtained by employing a small amount of regeneration[75] through a low-capacitance coupling, illustrated in Fig. 85. All four stages are occupied by screen-grid tubes. Figure 86 indicates how

well adapted the circuit is for securing low capacitance of connections and perfect screening.

Other methods. Naturally very many schemes for scanning in television have been devised, but we refer

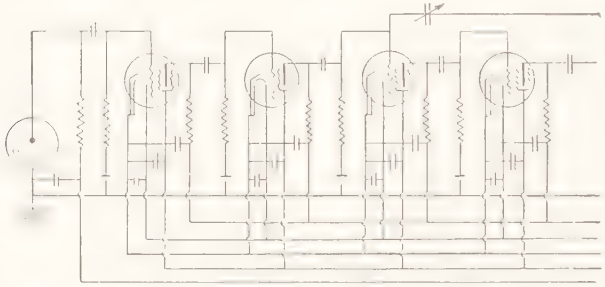

FIG. 85.—An alternative circuit for peaking high frequencies for a television amplifier.

the reader to the summary by A. Dauvillier[96] for an account of them. However, a method particularly convenient for scanning moving picture film has been developed by one of the authors.[97] A beam of light is swept

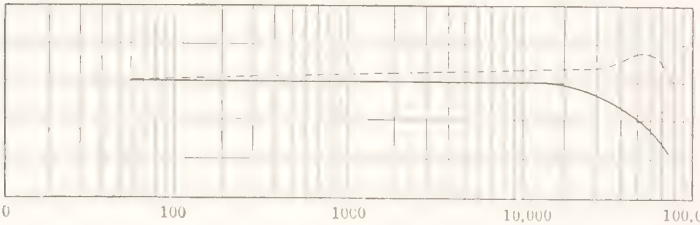

FIG. 86.—The dotted curve shows how high frequency losses may be neutralized by the proper introduction of capacitance as in Fig. 85.

back and forth across the film by a vibrating mirror, while the continuous travel of the film supplies the vertical component of scanning. The optical arrangement is sketched in Fig. 87. A photocell, placed behind the

film, receives the modulated light. To obviate distortion caused by chance variations of sensitivity over the surface of the cathode, a lens placed between film and cell focuses an image of the vibrating mirror on the cathode. Hence the scanning beam always strikes the same sensitive area.

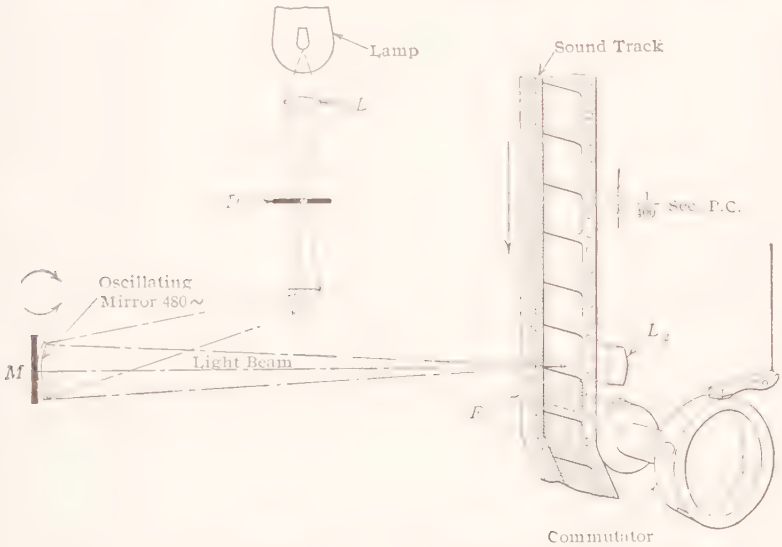

FIG. 87.—The optical arrangement in a novel method of scanning moving picture films.

Television receivers. The photocell plays no part at all in the reception of television signals sent out from a broadcasting station. If a short-wave radio receiver designed to pass the proper frequency band is tuned to the carrier of such broadcast signals, the loudspeaker will convert the impulses into a chaos of noisy sounds. If, however, the loudspeaker is replaced by a *flat-plate glow tube* properly connected, each change in signal will

produce a change in intensity of glow instantaneously over the whole area of the plate. To secure the televised picture, it is necessary only to rotate before the glow tube a Nipkow disk provided with the same number of holes as the one used at the transmitting station and to regulate the speed to coincide with that of the sending disk, and finally to shift its phase until the first hole starts across the glow-plate just as the sending disk starts to scan the object. When these conditions are satisfied, an image will be seen pictured in the glow.

A promising method of reception employing a Kerr cell is described by E. Schröter.[98]

In amateur receiving sets, the adjustment of speed and phase is rather uncomfortably maintained by *manual control*, but in more pretentious outfits, such synchronizing and "framing" are secured by remote control from the station through special broadcast impulses and special devices included in the receiving set.

A type of receiver which promises to compete favorably with all other types comprises a modified form of *cathode ray oscillograph* in which the picture appears on a fluorescent screen excited by a scanning beam of electrons controlled in intensity by the incoming signals.[97]

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CHAPTER XIII

MISCELLANEOUS APPLICATIONS

Within the last half century an endless number of uses for light-sensitive devices have been proposed, but it is only during the last few years that many of the ideas have reached consummation. The evident reason is that not until recently have photocells been made of sufficient sensitivity and reliability to be employed in practical circuits. Now that the photocell is beginning to win the confidence of designing engineers, its field of usefulness is just beginning to be explored. When the photocell becomes as familiar as the radio tube, its applications will be legion.

Out of the great number of miscellaneous applications of the photocell that have been actually made and that have been recorded in literature, we wish to select a few examples to serve as interesting illustrations of what distinct operations can be performed.

Contactless relay. Doubtless the most common application of the photocell is its function as a contactless relay. In any case where mechanical contact is inconvenient or even impossible, the photocell with accompanying light beam provides an easy solution of controlling operations. In combination either with a thermionic or grid-glow tube, as described in Chapter IX, the device becomes a sensitive and rugged commercial unit. The unit serves a useful purpose in *counting*

the number of articles turned out in mass production, persons passing through an entrance or exit, vehicles entering or leaving a tunnel, and so on to the limit of one's imagination. A picture of such a unit developed by Westinghouse [99] is shown in Fig. 88.

A similar device is employed together with standard colored lights to *traffic control* at busy intersections. It is conveniently installed at intersections of main highways with less important roads. In such instances, traffic is always open on the highway unless a vehicle

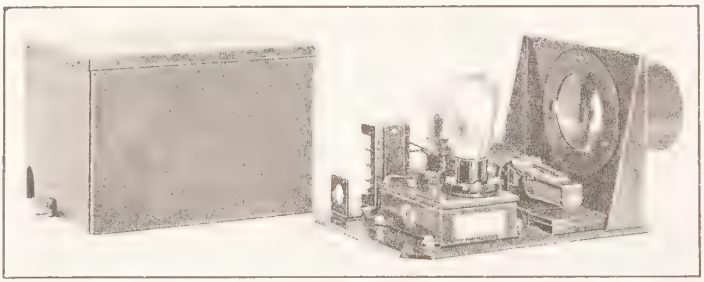

FIG. 88.—A photocell amplifier unit with many industrial applications.

approaches on the crossroad, in which event an interrupted light beam initiates a relay action to change the traffic lights.

Automatic inspection.—In visual inspection of industrial products, the human eye is not always capable of making close enough selections or gradations, and the eye becomes fatigued as the day progresses, so that the quality of the results of inspection is much different in the evening than in the morning. Not only can the photocell perform this visual inspection, but it can be made to do it with much greater accuracy and reliability. The inspection of *surfaces* by either the intensity or the

quality of light reflected into a photocell has become a commercial reality. If the article is small or can be caused to travel uniformly under an inspecting beam, the task of detection can be readily performed by the unit already described. When the surfaces are large, some sort of scanning method may be employed or else a bank of similar cells in series may inspect simultaneously an illuminated strip of the moving article. In the latter case diminution of light flux in any one of the cells limits the current through all alike.

How the photocell may be used to *check small departures in sizes* of manufactured articles is described by Robbins.[100]

Photometry of ultra-violet.—In Chapter IV mention was made of photocells especially designed for measuring the intensity of ultra-violet radiations. Harris[51] describes a practical circuit for amplifying the output of a cadmium cell so that total radiation from an ultra-violet source may be measured in terms of the current through a rugged micro-ammeter. The circuit is illustrated in Fig. 89. He publishes curves to show that cooling a vacuum mercury arc with a fan reduces its efficiency about 70 per cent, and that an arc with reflector may be actually less efficient than one without a reflector. His results also indicate that quartz is the only material among a list of supposedly transparent substances which really transmits ultra-violet beyond 3000 A.

For the measurement of the intensity of therapeutic radiations, a suitable device has been developed by H. C. Rentschler[52] of the Westinghouse Lamp Co. The uranium cell described in Chapter IV is included in the circuit shown in Fig. 90. The photocell battery charges

the condenser C at a rate determined by the photoelectric current, which is in turn proportional to the inten-

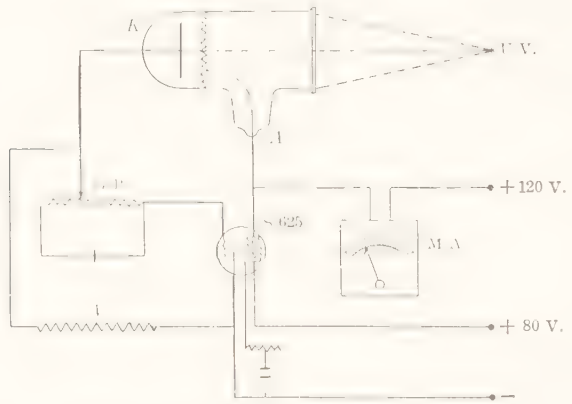

Fig. 89.—A diagram illustrating the use of a cadmium cell for measuring intensity of ultraviolet radiations.

sity of the exciting radiations. When the potential of the condenser reaches a certain critical value, the glow

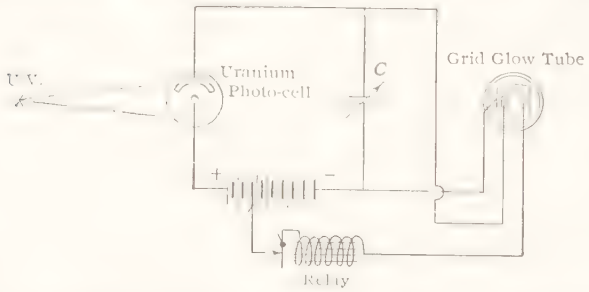

Fig. 90.—An ultraviolet intensity indicator employing a uranium photocell and a grid-glow tube.

tube breaks down, the condenser discharges, and a relay is operated to register a count of the discharge. The number of discharges per unit time corresponds to the

intensity of the radiations, and hence can be used as a measure of this intensity. A graphic meter may be substituted for the counter, and a continuous record may be obtained of the intensity of radiation. The device is assembled as a self-contained, portable outfit.

Color matching. Matching of colors is a task for which a photocell is inherently suited. Each type of cell has its own color-sensitivity curve which is even more constant than its current sensitivity. Auxiliary equipment is essentially the same as that used in standard color matching devices, but the photocell with a suitable indicator is substituted for the human eye. Bergstein [9] suggests a rather crude comparison box. The photocell and constant light source are in separate light-tight compartments of a metal box. Light is focused upon a sample and is then diffusely reflected through a filter into the cell. Current readings of the cell are taken for successive samples and with given filters. Only those samples are identical in color for which the photocell responses are the same with all the several filters.

Adjustment of lamps to color-match may be accomplished photoelectrically [9] by placing each lamp in turn so that it may illuminate simultaneously two cells of quite different color-sensitivity characteristics, and their currents are adjusted to equality. If a second lamp replaces the first, the cell currents will remain equal only if the two lamps have identical color temperatures.

Photometry of the visible. Figure 91 is a schematic diagram of a similar apparatus described by G. T. Winch [10] for measuring of color temperatures and also luminous intensities. When the cells are in series, as

shown, the ratio of the currents from the two cells of different color sensitivities gives a measure of variation in color temperature. The adjustment for balance is indicated by an electroscope. An improved circuit by the same investigator replaces the electroscope by a standard d-c amplifier.

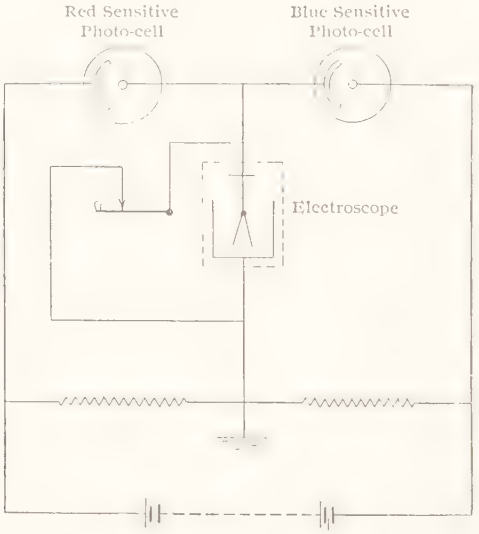

FIG. 91.—A schematic diagram of an apparatus for measuring both color temperature and luminous intensity.

By switching the connection of the photocells from series to parallel, the sums of the currents may be obtained as a relative measure of the luminous intensity of the source.

It is quite possible to select a type of photocell with a color-sensitivity closely resembling that of the eye; and indeed with proper filters the cell can be made as nearly like the eye as occasion may demand. This feature is of great importance in the automatic calibration

of secondary standard lamps for which the candlepower is by definition dependent on the color-sensitivity of the eye. Again, it is quite feasible to use two photocells in parallel so chosen that the effective sensitivity curve is flat for all colors. In general, absolute flatness can be obtained only by the additional use of selected filters. With such a combination the intensities of lights of two different colors may be directly compared with accuracy.

The linear response of a photocell with respect to the intensity of incident light flux makes it an ideal instrument for absolute measurements of the brightness of faint sources such as stars. Thus General Ferrie speaks of Vega and Capella in terms of microamperes.[101]

Color analysis. With the advent of sensitive photocells which are capable of responding throughout the entire visible spectrum, it has become possible to construct practical automatic color analyzers. An accurate, though rather complicated, analyzer has been designed by A. C. Hardy.[102] A schematic diagram of his device is shown in Fig. 92. Essentially, light from opposite sides of an incandescent tungsten ribbon illuminates a standard surface of magnesium carbonate and the surface of the sample to be analyzed. Diffusely reflected light from both surfaces is projected in rapid alternation through a monochromator into the cell. An automatic mechanism controlled by the output of the cell records on a drum the ratio of the energy reflected from the sample to that from the standard for various wavelengths. The device is constant enough to retrace a record without appreciably widening the original pen line, and accurate enough to check Bureau of Standards data for a glass filter. It is independent of the shape of the color-sensitivity curve of the cell.

A simpler recording color analyzer, which has the advantage of being portable, has been built by P. J. Mulder and J. Razek.[100] In this instrument the sample is placed at the center of a luminous hemisphere, and the reflected light passes through a monochromator to the photocell. One slit is automatically adjusted in width to compensate for variable dispersion of the prism, while the other slit is adjusted in length to compensate for the color-sensitivity characteristic of the photocell.

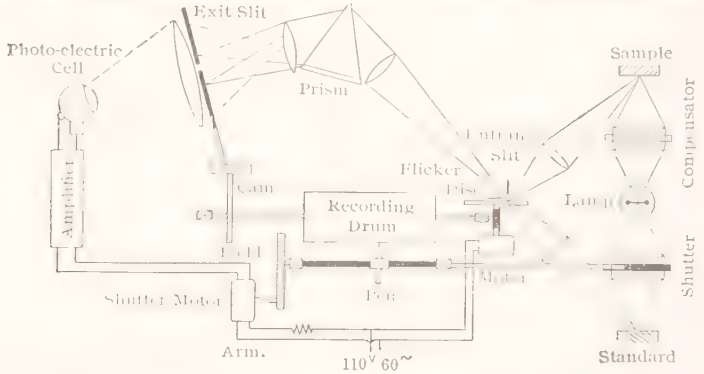

FIG. 92.—A completely automatic color analyzer. (After Hardy, by courtesy of J. O. S. A. and R. S. I.)

The analyzer is calibrated with a standard surface, and then the reflectivity of a sample is photographically recorded on paper or film, or may be observed visually.

Automatic controls.—The fact that a cell is ordinarily not flat in color response is used to advantage in both qualitative and quantitative measurements upon colored liquids and solutions encountered in the chemical industries. For example, automatic *titration* can be controlled by the photocell.[101]

Time recording.—Again, a good illustration of the honorable position acquired by the photocell in impor-

tant operations is its use for recording the *passage of a star* over a given meridian and hence for setting the clocks of the world. For this purpose the cell is placed behind the collimator slit of an astronomical telescope. A hair line is focused at the middle of the slit. When the image of a star comes upon one edge of the slit, the light passing the edge is used to produce a musical note in an auxiliary device connected to the cell. When the image of the star coincides precisely with the hair line, the light and hence the musical note are interrupted. At the same time a photographic record is made of the transit. The accuracy obtained is many times greater than that secured by visual observation.

One can readily see how a photocell may be utilized in recording *swings of the pendulum* in a precision clock without in anywise producing a retarding torque.[107]

Illumination recording. -For *integrating* the total amount of light emitted by a given source over any period of time, L. R. Koller[108] has developed a unit consisting of a photocell in series with a battery and a hydrogen voltameter. The total quantity of electricity passed by the cell is accurately recorded by the volume of the hydrogen liberated at the cathode of the voltameter. In this way, for example, daily computations may be made of average daylight illumination. *Instantaneous values of illumination* may also be obtained by using a sensitive recording meter.

Photoelectric dividing machine. Many of our readers are doubtless familiar with the nature of an optical grating which is used in many forms of spectrographs for producing diffraction spectra of a given light source. The ruling of good gratings such as those made by Rowland has heretofore required the tedious preparation of

an almost perfect screw for advancing the ruling point through a precise interval between successive lines. Gramont has designed a ruling machine which is capable of spacing the ruled lines with uniform intervals of a definite number of wavelengths of light. The machine involves the use of an *interferometer*, one mirror being mounted on the carriage which supports the grating and the other mirror being rigidly fixed to the frame. Motion of the carriage causes interference rings to precede across a slot in front of a photocell, and a special relay is arranged to stop the motion of advancement after a definite number of rings have passed. The ruling point then scribes a line, after which the carriage again advances through precisely the same interval. Thus uniform grating spaces, equal in width to a definite number of half-wavelengths, are secured without the necessity of an accurate screw.

Calibration of meters. A clever and precise method for calibrating watt-hour meters is described by Aronoff and Young.[109] A beam of light is focused upon the slotted periphery of the rotating disk of a standard meter, Fig. 93. Thus the light which enters a photocell situated beneath the disk is modulated with a frequency determined by the speed of rotation. The pulsating current in the cell is amplified and fed into a glow tube which is caused to illuminate the notched rim of the rotating disk of the meter to be calibrated. The number of notches is equal to the number of slots in the standard disk. The calibrating mechanism of the second meter is adjusted until its disk appears to be stationary. (See Fig 94.) Under this condition its speed is precisely the same as that of the standard. It is understood that both meters are supplied with the same

energy. Modifications of this ingenious scheme appear to be innumerable.

Photocell-galvanometer combination. Another application capable of numerous modifications is the combination of a photocell with a galvanometer provided with a mirror. An arrangement for controlling furnace temperatures can be found in an article by Arnold.[110] A thermocouple in the furnace produces a definite deflec-

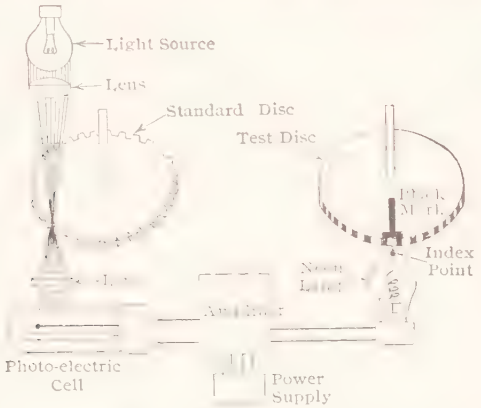

FIG. 93.—A schematic diagram of a photoelectric device for calibrating watt-hour meters.

tion of the galvanometer so that its mirror reflects a beam of light in a definite direction. A photocell is placed so that any further deflection of the galvanometer sends the light into the cell and activates a device for controlling the heating current or fuel supply. By using two photocells in opposition and adjusting the beam initially to illuminate both equally, a double-acting control may be obtained.

Safety devices. One of the earliest uses to which photocells were put was in safety devices for *smoke*

detection and *fire prevention*. A cell, conveniently located in a building so as to be properly shielded from excess daylight and artificial illumination, is capable of detecting spurious radiation from a starting fire and can be

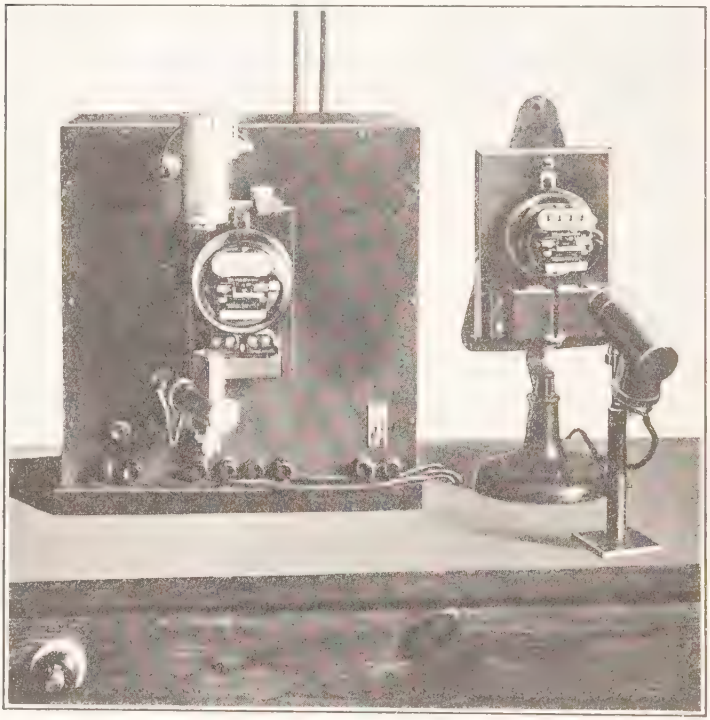

FIG. 94.—A photoelectric device for calibrating watt-hour meters.

caused to operate an alarm or extinguishing apparatus. For smoke detection, a beam of light is directed into the cell through the space to be protected. Any smoke arising will obscure the light and change the output of the cell, which can in turn operate a relay. A convenient circuit for this purpose involving a grid-glow tube

is shown in Fig. 95. In this unit the glow tube is activated when the illumination is decreased.

Exactly the same unit can be used as a *burglar alarm*, in which case the beam is interrupted by the passing of a human body.

Other safety device applications, such as the *stopping of machinery* when a danger point is reached or when a break occurs in some part, will suggest themselves.

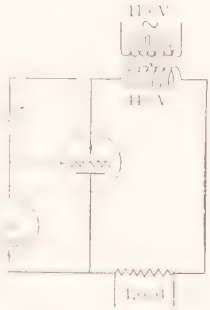

Fig. 95.—A convenient circuit for a photoelectric relay for burglar alarm.

Measurement of high-frequency currents.—An instructive application of the photocell was made by Byrnes [111] in the measurement of very high-frequency currents. Assuming that the brightness of a tungsten filament in a lamp depends only on the effective current, provided the frequency is high with respect to the heat capacity of the filament, such a lamp may be calibrated with d-c current in terms of photocell response. Thus with a calibrated lamp or bank of lamps introduced in the high-frequency load circuit, the photocell response determines immediately the unknown current.

Communication. A most interesting accomplishment made successful by the photocell is the communication of intelligence over a directed beam of light. As a matter of fact, a beam of light, modulated by the human voice and detected by a selenium cell, was actually the precursor of modern telephony. Graham Bell experimented with communication over light prior to his invention of the wired telephone. In recent times the same scheme improved by the substitution of a

photocell and amplifier for selenium cell and earphones has presented a convenient means for telegraphic, telephonic and facsimile transmission over short distances. The greatest distance over which intelligence may be transmitted depends only on how far a modulated beam can be optically projected with sufficient intensity to energize a photocell. Practical use has been made of light-beam transmission for military communication at sea.

A valuable modification is to employ an invisible radiation either of ultra-violet or infra-red. Infra-red is of particular promise as a medium of transmission because of its ability to penetrate fog, smoke or dust better than radiation of shorter wavelength. Modern photocells, such as the cesium-oxide cell, which have a peak of sensitivity in the near infra-red, are quite suitable as detectors of these radiations.

Recently success has been claimed by Baird [112] in the transmission by television of objects illuminated only by infra-red radiations.

Mechanical reading.—As a final illustration of the many roles played by the photocell in the service of humanity, we wish to describe briefly a reading device in which a photocell is the substitute for a human eye. In 1914 Fournier d'Albe [113] invented an instrument which actually made it possible for a blind person to read by the use of his sense of hearing! The operation of the device, which d'Albe called an "*optophone*," is based mainly upon the reception by a photo-sensitive element (originally a selenium cell) of light scattered from a printed page, much in the same manner as described for facsimile transmission. Figure 96 gives a sketch of the optical system by means of which the page

is illuminated. A light chopper containing five concentric circles of holes, each circle being perforated with a different number of holes, divides the light into five

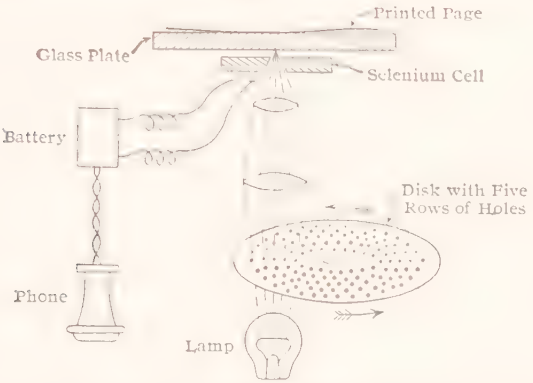

FIG. 96.—D'Albe's system for converting a printed page into musical chords.

separate beams. These beams are focused into five spots closely arrayed in a straight line along the height of the printed characters. As the page is moved sidewise, the spots of light, each of a different frequency,

FIG. 97.—The scanning paths followed by the beams of the Octophone.

effectively peruse the printed line in a manner illustrated in Fig. 97. In a white space all five spots reflect light to the sensitive element and produce a current composed of five frequencies which ultimately cause a composite tone in a set of phones. However, when the

spots are partly absorbed by the black characters, the tone in the phones changes in a manner peculiar to the particular letter being scanned. Within a period of a few months, a blind person may be taught to read common print at a rate as high as sixty words a minute.

A similar machine invented by B. Rosing [114] and built like a typewriter, employs a photocell to interpret printed characters into a series of musical notes.

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CHAPTER XIV

PHOTOCELLS IN THE FUTURE

It is natural for us to wonder what the future may hold in store for the photocell, once a swaddling infant of little promise and now a lusty child of rapid growth. It will be recalled that the earliest photo-emissive phenomena were scarcely detectable by a gold leaf electroscope. Brightly polished surfaces of zinc or aluminum quickly tarnished under the effect of ultra-violet radiation, and photo-emission decreased quite rapidly to an inappreciable fraction of its initial value. Just as soon as Elster and Geitel found that a surface of amalgamated zinc retained its emissive power with reasonable constancy over a period of several hours, and could then be rejuvenated by fresh application of mercury, they were ready to suggest the use of such a surface in ultra-violet photometry. The enclosed copper oxide cell of Hallwachs, remaining constant for months, added incentive to photoelectric photometry of the ultra-violet.

Consistently with a law of scientific progress, the improvement in photo-emissive surface had led to definite applications. In further obedience of the law, these applications gave new impetus to the development of better cells which would accomplish results not obtainable at the time, such as photometry of visible radiations. The desire resulted in the discovery of the sensitivity of the alkali metals to ordinary light; and again,

the new characteristics of alkali cells suggested new uses for photo-sensitive units.

Thus, hand in hand, the two comrades Development and Application stride down through the decades, first one and then the other slightly to the fore. By now, the practical values of current passed by photocells, and the satisfactory stability and longevity assured, have gained the confidence of designing engineers and in general a wider scope of public interest. The natural result is the multiplication both in number and kinds of applications.

It would indeed be quite unusual if the following decades would not carry on the traditions of the past. We must expect a great improvement not only in the effective sensitivity of photocells, but also in the auxiliary equipment used in conjunction with them. Greater sensitivity, greater simplicity, greater efficiency will be the general contribution of the future.

Probable advancement. It would be unwise to make any definite prediction as to the actual results that will be achieved, but it may be instructive to point out the direction in which advancement will doubtless take place.

It might occur to the reader that since most metals are photo-sensitive to ultra-violet and that some of the most recent types of cells also have decided peaks of response in this short wavelength region, it should be logical to take advantage of this fact and develop schemes of using ultra-violet in future devices. Second thought, however, will present three very good reasons why this would not be wise. First, the only practical source of ultra-violet which has reasonable intensity is the quartz mercury arc. This source is expensive and

cannot compare with the ordinary electric lamp in case of manipulation. Second, the entire optical system would have to be made up of parts translucent to short waves. For example, in sound movies quartz lenses would be needed and a different type of film. Third, ultra-violet radiations are harmful to the eyes, so that special precautionary measures would be essential. The second reason will be greatly weakened if we confine our attention only to the near ultra-violet, say the spectral

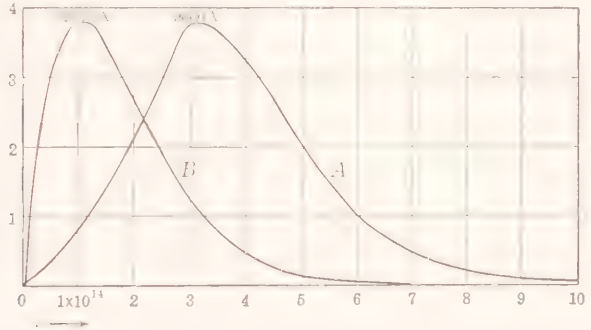

FIG. 98.—Curve A represents the distribution of photons emitted by a black body at 3000° K. Curve B represents the distribution of energy from the same source.

region between 3000 A and 4000 A. Glass and film are relatively transparent to these radiations.

A fourth reason why it would not be wise to deal with the ultra-violet, or even with the visible, is of a more fundamental nature and will become apparent in the following paragraphs.

In Fig. 98, curve A represents the distribution of energy as emitted by an ideal black body at 3000 absolute temperature, as described in Chapter II. Here the relative energy radiated at each frequency is plotted as a function of the frequency. It will be observed that

the greatest amount of energy is being radiated at a frequency corresponding to a wave-length of about 9000 Å in the near infra-red. As was previously pointed out, since normal light sources have distributions similar to that of a black body, it is desirable for that reason alone to attempt to develop cells with maximum sensitivity at longer wavelengths. It is of great significance also to observe how feeble the radiation is for wavelengths shorter than 4000 Å.

Distribution of photons. But now we arrive at a consideration which is generally ignored, but which should be of prime importance. It has been established that the relation between radiation and release of electrons is of a quantum nature. Each time an electron is emitted, a quantum of energy or photon is absorbed for the purpose. Now the size of a photon is $h\nu$ and is obviously a linear function of the frequency. Hence for a monochromatic radiation of a given frequency and given energy content, there will exist a definite number of photons determined by dividing the total energy of the radiation by the energy of each photon. For example, consider an erg of yellow light from the sodium spectrum. Assume the frequency to be 5.09×10^{14} corresponding to a wavelength of 5893 Å. The photon will have an energy of $h\nu = 6.55 \times 10^{-27} \times 5.09 \times 10^{14} = 3.33 \times 10^{-12}$ erg. The total number of photons is then $1/3.33 \times 10^{-12} = 3 \times 10^{11}$. In other words, an erg of sodium light comprises 300 billion quanta of energy.

In general, for a given energy of radiation, the number of photons increases with the wavelength. Curve *B* of Fig. 98 gives the distribution of photons in black-body radiation at 3000° absolute. The important fact

to observe is that there are relatively no photons in the ultra-violet and that the greatest number of photons are found at about 30,000 Å or 3 μ. The maximum in the photon curve is even still farther in the infra-red than is the peak of the energy curve.

The ideal cell. Assuming now that the greatest possible number of electrons will be released by the greatest possible number of photons, provided that each photon has sufficient energy to free an electron and that each photon has access to a separate electron, it will appear that the ideal photocell must be one which has maximum sensitivity at 30,000 Å. A slightly shorter wavelength for the peak results if we allow for the actual energy curve for tungsten instead of for a black body.

It might prove of value to estimate what the ideal limit is for the number of electrons released by one erg of energy from a black body at 3000° C., under the assumption that every photon releases one electron. The total number of photons emitted by the source is found by mathematical calculation to be 9×10^{14}.* Taking the electronic charge as 1.59×10^{-19} coulomb, the total quantity of electricity liberated from the surface would be 1.43×10^{-5} coulomb. If a voltage should be applied between the surface and a collector so that all the electrons would move to the anode, and if the black body is emitting the erg during one second, the current in the ideal photocell would be 0.143 microampere. For radiation at the rate of 1 watt, the current would be 1.43 ampere. Since the energy curve for a tungsten lamp has nearly the same shape as that for a black body, the above value would still be approximately valid except for the fact that glass vessels in which not only

* See the Appendix for mathematical computations.

filaments but also photo-sensitive surfaces are enclosed are not transparent to all frequencies. If we cut off all frequencies below 10^{14} and above 10^{15}, leaving just the range corresponding to the limits 3000 A to 30,000 A, the maximum response is about two-thirds the ideal, namely, about 1 ampere per watt of incident radiation. Taking roughly that a Mazda lamp radiates 80 per cent of its supplied power, and counting 1 candlepower per watt of supplied power, we may allow about 1.2 candlepower per watt of radiant energy. Thus 1 lumen of light flux will correspond to approximately 0.066 watt radiation from a lamp at 3000° absolute. Finally, then, we are able to deduce that the ideal photocell in an evacuated glass bulb should have a sensitivity corresponding nearly to 66 milliamperes per lumen, a value 2000 times as high as that obtained in our best vacuum cells.

Whether this limit may or may not be closely approached is impossible to predict, but certainly cells have been improved by a factor much greater than that since the early days, provided we speak in terms of a metallic filament lamp at the temperature cited. Many practical and some theoretical limitations will present themselves, but that has always occurred with every development. An illustration comes to mind of the possible thermionic emission from such a photocell even at room temperatures. This spurious current would decrease the impedance of the cell and lower the optimum output, which after all is the quantity to be elevated in practice. On the other hand, it is quite reasonable to presume that a thermionic emission from the photo-sensitive cathode could be used to advantage in some sort of amplification.

Infra-red detection. The fact that cells can now be made with maximum sensitivity in practically any part of the visible spectrum or in the ultra-violet and near infra-red naturally suggests the probable use of cells with suitable filters, not only for refined color selectors or color comparators, but also in many other devices as super-sensitive ocular "resonators" or detectors. The feat of transmitting and receiving television in natural colors has already been accomplished with a certain degree of success.

The present indications are, however, that attention will be focused upon the infra-red region of the spectrum. The cells that will ultimately be developed will respond most readily to heat radiations that are totally invisible to the human eye. The natural application will be *nocturnal vision*. It is not at all fantastic to expect a simplified form of television apparatus which will pick up heat radiations from invisible physical objects and transform them into visible outlines on a suitable screen. Baird has described a kind of infra-red television which indicates the inherent possibilities of such a scheme.

It would be easy to venture predictions as to results that will be achieved which would be astounding to us at present, but we refrain from hazarding any guesses, even though experience has shown that past prophets have been modest enough in their supposedly rash envisages.

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APPENDIX

ILLUMINATING ENGINEERING NOMENCLATURE AND PHOTOMETRIC STANDARDS

(*Selected from Transactions of Illuminating Engineering Society*, 20, 629, 1925.)

1. Light: The term light is used in various ways:

(*a*) To express the visual sensation produced normally when radiant flux (q.v.) within the proper limits of wavelength, of sufficient intensity and of sufficient duration, impinges on the retina.

(*b*) To denote the luminous flux (q.v.) which produces the visual sensation.

(*c*) By extension, even to denote radiant flux of wavelengths outside of the visible spectrum (for example, ultra-violet light).

2. Radiant Flux is the rate of energy radiation, and is expressed in ergs per second or in watts.

3. Luminous flux is the rate of passage of radiant energy evaluated by reference to the luminous sensation produced by it.

When the rate is constant as is usual in practical photometry, luminous flux as defined above is often considered as an entity or quantity. The term luminous flux, and also the general name light, are often used without discriminating between the rate of passage and the time-integral of that rate, or the quantity of light. In precise quantitative statements, it is necessary to distinguish between flux, which is the rate, and quantity, which is the time integral of it.

4. Lumen.—The unit of luminous flux is the lumen. It is equal to the flux emitted in a unit solid angle by a uniform point source of one international candle.

5. The Luminous intensity of a point source in any direction is the luminous flux per unit solid angle emitted by that source in that direction.

The flux emanating from a source whose dimensions are negligible in comparison with the distance from which it is observed may be considered as coming from a point.

6. International candle.—The unit of luminous intensity is the international candle, such as resulted from agreements effected between the

three National Standardizing Laboratories of France, Great Britain, and the United States in 1909.

This unit has been maintained since then by means of incandescent electric lamps in these laboratories which continue to be entrusted with its maintenance.

7. Candlepower is luminous intensity expressed in candles.

8. The illumination at a point of a surface is the density of the luminous flux incident at that point or the quotient of the incident flux by the area of the surface when the latter is uniformly illuminated.

9. Lux.—The practical unit of illumination is the lux. It is the illumination of a surface one square meter in area receiving a uniformly distributed flux of one lumen, or the illumination produced at the surface of a sphere having a radius of one meter by a uniform point source of one international candle situated at its center.

In view of certain recognized usages, illumination may also be expressed in terms of the units phot and foot-candle.

10. Phot.—Taking the centimeter as the unit of length, the unit of illumination is the lumen per square centimeter; it is known as the Phot.

11. Foot-candle.—Taking the foot as the unit of length, the unit of illumination is the lumen per square foot; it is known as the Foot-candle.

$$1 \text{ foot-candle} = \begin{cases} 10.764 \text{ lux} \\ 1.0764 \text{ milliphot} \end{cases}$$

12. Quantity of light is the product of luminous flux by the time it is maintained. It is the time integral of luminous flux.

13. The lumen-hour is the unit of quantity of light. It is equal to a flux of one lumen continued for one hour.

14. The brightness in a given direction of a surface emitting light is the quotient of the luminous intensity measured in that direction by the area of this surface projected on a plane perpendicular to the direction considered.

15. Units of brightness: The practice recognized internationally is to express brightness in international candles per unit area of surface. The brightness of any surface, in a specified direction, can also be expressed in terms of the lumens per unit area emitted by a perfectly diffusing surface of equal brightness.

In practice no surface obeys exactly the cosine law of emission or reflection; hence the brightness of a surface generally is not uniform but varies with the angle at which it is viewed.

16. The lambert is the average brightness of any surface emitting or reflecting one lumen per square centimeter, or the uniform brightness of a

perfectly diffusing surface emitting or reflecting one lumen per square centimeter.

For most purposes the millilambert, 0.001 lambert, is the preferable practical unit.

Brightness expressed in candles per square centimeter may be reduced to lamberts by multiplying by π.

Brightness expressed in candles per square inch may be reduced to lamberts by multiplying by π 6.45 = 0.487.

17. The foot-lambert is the average brightness of any surface emitting or reflecting one lumen per square foot, or the uniform brightness of a perfectly diffusing surface emitting or reflecting one lumen per square foot.

A completely reflecting surface under an illumination of one foot-candle, therefore, has an average brightness of one foot-lambert; the average brightness of any surface in foot-lamberts is the product of the illumination in foot-candles by the reflection factor of the surface.

One foot-lambert is equal to 1.076 millilamberts.

One foot-lambert is equal to 1 144 candles per square inch; brightness expressed in candles per square inch may, therefore, be reduced to foot-lamberts by multiplying by 452.

18. The visibility factor for radiation of a particular wavelength is the ratio of the luminous flux at that wavelength to the corresponding radiant flux.

19. The relative visibility factor for a particular wavelength is the ratio of the visibility factor for that wavelength to the maximum value of the visibility factor.

20. A luminosity curve of a source of light is a curve showing for each wavelength the luminous flux per element of wavelength. Therefore, it gives, wavelength by wavelength, the product of the radiant flux and the visibility.

21. The luminous efficiency of the radiation from any source is the ratio of the luminous flux to the radiant flux from the source. For practical purposes it is usually expressed in lumens per watt of radiation. This should not be confused with the term efficiency as applied to a practical source of light.

THE CHEMICAL ELEMENTS BY ATOMIC NUMBER

Atomic Number	Element	Symbol	Atomic Weight	Atomic Number	Element	Symbol	Atomic Weight
1	Hydrogen	H	1.008	47	Silver	Ag	107.88
2	Helium	He	4.00	48	Cadmium	Cd	112.4
3	Lithium	Li	6.94	49	Indium	In	114.8
4	Beryllium	Be	9.02	50	Tin	Sn	118.7
5	Boron	B	10.82	51	Antimony	Sb	121.8
6	Carbon	C	12.00	52	Tellurium	Te	127.5
7	Nitrogen	N	14.008	53	Iodine	I	126.92
8	Oxygen	O	16.000	54	Xenon	Xe	130.2
9	Fluorine	F	19.00	55	Cesium	Cs	132.8
10	Neon	Ne	20.2	56	Barium	Ba	137.4
11	Sodium	Na	23.00	57	Lanthanum	La	138.9
12	Magnesium	Mg	24.32	58	Cerium	Ce	140.2
13	Aluminium	Al	26.97	59	Praseodymium	Pr	140.9
14	Silicon	Si	28.06	60	Neodymium	Nd	144.3
15	Phosphorus	P	31.04	61			
16	Sulphur	S	32.07	62	Samarium	Sm	150.4
17	Chlorine	Cl	35.46	63	Europium	Eu	152.0
18	Argon	Ar	39.88	64	Gadolinium	Gd	157.3
19	Potassium	K	39.10	65	Terbium	Tb	159.2
20	Calcium	Ca	40.07	66	Dysprosium	Dy	162.5
21	Scandium	Sc	45.10	67	Holmium	Ho	163.5
22	Titanium	Ti	48.1	68	Erbium	Er	167.7
23	Vanadium	V	51.0	69	Thulium	Tm	169.4
24	Chromium	Cr	52.01	70	Ytterbium	Yb	173.5
25	Manganese	Mn	54.93	71	Lutecium	Lu	175.0
26	Iron	Fe	55.84	72	Hafnium	Hf	178.6
27	Cobalt	Co	58.97	73	Tantalum	Ta	181.5
28	Nickel	Ni	58.68	74	Tungsten	W	184.0
29	Copper	Cu	63.57	75	Rhenium	Re	
30	Zinc	Zn	65.37	76	Osmium	Os	190.9
31	Gallium	Ga	69.72	77	Iridium	Ir	193.1
32	Germanium	Ge	72.60	78	Platinum	Pt	195.2
33	Arsenic	As	74.96	79	Gold	Au	197.2
34	Selenium	Se	79.2	80	Mercury	Hg	200.6
35	Bromine	Br	79.92	81	Thallium	Tl	204.4
36	Krypton	Kr	82.9	82	Lead	Pb	207.2
37	Rubidium	Rb	85.5	83	Bismuth	Bi	209.0
38	Strontium	Sr	87.6	84	Polonium	Po	210
39	Yttrium	Yt	89.0	85			
40	Zirconium	Zr	91.2	86	Niton	Nt	222
41	Niobium	Nb	93.5	87			
42	Molybdenum	Mo	96.0	88	Radium	Ra	226.0
43	Masurium	Ma		89	Actinium	Ac	
44	Ruthenium	Ru	101.7	90	Thorium	Th	232.1
45	Rhodium	Rh	102.9	91	Protactinium	Pa	
46	Palladium	Pd	106.7	92	Uranium	U	238 2

HARMONICS IN THE PHOTOCELL CURRENT

(Cf. p. 96)

Beginning with the expression

$$i = \frac{EGl}{GZ_0l + 1}$$

We may alter the form of the right member as follows:

$$i = \frac{E}{Z_0}\left(\frac{GZ_0l}{GZ_0l + 1}\right) = \frac{E}{Z_0}\left(1 - \frac{1}{GZ_0l + 1}\right)$$

Substituting $l = \frac{1}{2}L\ (\sin \omega t + 1)$,

$$i = \frac{E}{Z_0}\left(1 - \frac{2}{GZ_0L\ (\sin \omega t + 1) + 2}\right)$$

$$= \frac{E}{Z_0}\left(1 - \frac{2}{(GZ_0L + 2) + GZ_0L \sin \omega t}\right)$$

Setting $GZ_0L = b$ and $GZ_0L + 2 = a$, the equation reduces to

$$i = \frac{E}{Z_0}\left(1 - \frac{2}{a + b \sin \omega t}\right)$$

Expanding by the binominal theorem,

$$i = \frac{E}{Z_0}\left[1 - \frac{2}{a}\sum_{n=0}^{n=\infty}\left(\frac{bj^2}{a} \sin \omega t\right)^n\right]$$

where $j^2 = -1$. If we assume that $(b/a)^2 < 0.1$, the function may be trigonometrically expanded into the Fourier's series.

$$i = \frac{E}{Z_0}\left[1 - \frac{2}{a}\left(1 + \frac{b^2}{2a^2} + \frac{3b^4}{8a^4}\right) - \left(\frac{b}{a} + \frac{3b^3}{4a^3} + \frac{5b^5}{8a^5}\right)\sin \omega t\right.$$

$$\left. - \left(\frac{b^2}{2a^2} + \frac{b^4}{2a^4}\right) \cos 2\omega t + \left(\frac{b^3}{4a^3} + \frac{5b^5}{16a^5}\right) \sin 3\omega t\right]$$

The ratios of the coefficients of $\cos 2\omega t$ and of $\sin 3\omega t$ to the coefficient of $\sin \omega t$ give respectively the percentage second and third harmonics present in the output.

DISTRIBUTION OF PHOTONS FROM A BLACK BODY

(Cf. p. 172)

An accurate mathematical expression for the distribution of energy from a black body is Planck's formula:

$$E = \frac{8\pi h}{c^3} \frac{\nu^3}{e^{h\nu/RT} - 1}$$

If, for purpose of simplification, we set $h\nu / RT = x$, and integrate over all frequencies from 0 to ∞, we obtain for the total density of radiation,

$$E = \int_0^\infty E_\nu d\nu = \frac{8\pi R^4 T^4}{c^3 h^3} \int_0^\infty \frac{x^3 dx}{e^x - 1}$$

Planck has evaluated this integral, the result being,

$$E = \frac{8\pi^5 R^4}{15 c^3 h^3} \cdot T^4$$

Assume a black body at a temperature T which is emitting energy at the rate of 1 erg per second. Then the distribution of photons may be computed directly from the obvious relation:

$$N_\nu = \frac{E_\nu}{E} \frac{1}{h\nu}$$

$$= \frac{15h}{\pi^4 R^4 T^4} \frac{x^2}{e^x - 1}$$

To determine the total number of photons per erg per second, N_ν may be integrated over the entire range of frequencies.

$$N = \int_0^\infty N_\nu d\nu = \frac{15}{\pi^4 RT} \int_0^\infty \frac{x^2 dx}{e^x - 1}$$

Now

$$\int_0^\infty \frac{x^2 dx}{e^x - 1} = \int_0^\infty x^2 (e^{-x} + e^{-2x} + e^{-3x} + \dots) dx$$

The expression is composed of integrals of the type

$$\int_0^\infty x^2 e^{-ax} dx$$

Integrating by parts,

$$\int_0^\infty \left(\frac{x^3}{e^x-1}\right) dx = \left[\frac{x^3}{3}\left(\frac{1}{e^x-1}\right)\right]_0^\infty + \int_0^\infty \frac{x^2}{3}\left(\frac{e^x}{e^x-1}\right) dx$$

$$= \frac{2}{3}\int_0^\infty \frac{x^2 e^x}{e^x-1}\, dx$$

Hence

$$\int_0^\infty \frac{x^2 e^x}{e^x-1}\, dx = 3\left(1 + \frac{1}{2^3} + \frac{1}{3^3} + \frac{1}{4^3} + \frac{1}{5^3} + \cdots\right)$$

$$= 2.404$$

Substituting in the original expression,

$$N = \frac{15}{\pi^4} \cdot 2.404$$

$$2.70 \times 10^{15} \times \frac{1}{T}$$

For a temperature of 3000° absolute,

$$N = 9.0 \times 10^{11} \text{ photons per erg per sec.}$$

If we assume that glass envelopes can transmit radiations only within the range of frequencies 10^{14} to 10^{15}, the above definite integral assumes the value of about 1.68, and N becomes

$$N = 6.3 \times 10^{11}$$

MEAN FREE PATHS

The mean free path of a molecule in an atmosphere of molecules of its own kind may be calculated from the formula,

$$L = 12.86 \frac{\eta}{p}\sqrt{\frac{T}{M}}$$

where η is the viscosity of the gas in c.g.s. units, is the pressure in mm., T is the absolute temperature, and M is the molecular weight. The following table records the mean free paths for a number of gases at various pressures.

Gas	20° C.	M	L in cm.		
			$p = 760$ mm.	$p = 1$ mm.	$p = 10^{-6}$ mm.
H_2	886	2.01	17.4×10^{-5}	13.8×10^{-3}	13,800
He	1964	4.0	25.2	19.2	19,200
Ne	3115	20.2	19.4	14.7	14,700
A	2239	39.9	9.9	7.5	7,500
Kr	2440	82.9	7.5	5.6	5,600
Xe	2204	130.2	5.4	4.1	4,100
N_2	1764	28.0	9.3	7.1	7,100
O_2	2018	32.0	9.9	7.6	7,600
Air	1809	.....	9.4	7.1	7,100

Period	Group I a	Group I b	Group II a	Group II b	Group III a	Group III b	Group IV a	Group IV b	Group V a	Group V b	Group VI a	Group VI b	Group VII a	Group VII b	Group VIII a	Group VIII b
I													1 H *1.008*			2 He *4.00*
II	3 Li *6.94*		4 Be *9.01*		5 *10.8*		6 C *12.00*		7 N *14.008*		8 O *16.000*		9 F *19.00*			10 Ne *20.2*
III	11 Na *23.00*		12 Mg *24.32*		13 Al *26.97*		14 Si *28.6*		15 P *31.04*		16 S *32.07*		17 Cl *35.46*			18 Ar *39.88*
IV	19 K *39.10*	29 Cu *63.57*	20 Ca *40.07*	30 Zn *65.37*	21 Sc *45.10*	31 Ga *69.72*	22 Ti *48.1*	32 Ge *72.60*	23 V *51.0*	33 As *74.96*	24 Cr *52.0*	34 Se *79.2*	25 Mn *54.93*	35 Br *79.92*	26 Fe *55.84* 27 Co *58.97* 28 Ni *58.68*	36 Kr *82.9*
V	37 Rb *85.5*	47 Ag *107.88*	38 Sr *87.6*	48 Cd *112.4*	39 Yt *89.0*	49 In *114.8*	40 Zr *91.2*	50 Sn *118.7*	41 Nb *93.5*	51 Sb *121.8*	42 Mo *96.0*	52 Te *127.5*	43 Ma	53 I *126.92*	44 Ru *101.7* 45 Rh *102.9* 46 Pd *106.7*	54 Xe *130.2*
VI	55 Cs *132.8*	79 Au *197.2*	56 Ba *137.4*	80 Hg *200.*	57 to 71 *Rare earths	81 Tl *204.1*	72 Hf *178.6*	82 Pb *207.1*	73 Ta *181.5*	83 Bi *208.0*	74 W *184.0*	84 Po *?*	75 Re	85—	76 Os *190.9* 77 Ir *193.1* 78 Pt *195.2*	86 Nt
VII	87—		88 Ra *226.*		89 Ac		90 Th *232.1*		91 Pa		92 U *238.2*					

* Rare earths

VI 57-71	57 La *138.9*	58 Ce *140.2*	59 Pr *140.9*	60 Nd *144.3*	61— ..	62 Sm *150.4*	63 Eu *152.0*	64 Gd *157.3*	65 Tb *159.2*	66 Dy *162.5*	67 Ho *163.5*	68 Er *167.7*	69 Tm *169.4*	70 Yb *173.5*	71 Cp *175.0*

ATOMIC AND ELECTRONIC CONSTANTS

(Dushman, High Vacuum)

Volume per gram-molecular weight of ideal gas:
At 0° C. and 1.01323×10^6 bars (760 mm. Hg)

$$V = 22{,}412 \text{ cm.}^3$$

At 0° C. and 1×10^6 bars (750 mm. Hg)

$$V = 22{,}708 \text{ cm.}^3$$

Gas constant

$$PV/T = R = 83.15 \times 10^6 \text{ erg/deg.} = 1.987 \text{ cal./deg.}$$

Faraday constant,

$$F = 96{,}500 \text{ coulombs}$$

Unit electric charge,

$$e = 4.774 \times 10^{-10} \text{e.s.u.} = 1.591 \times 10^{-20} \text{ e.m.u.}$$

Number of molecules per gram-molecular weight,

$$F/e = N = 6.062 \times 10^{23}$$

Number of molecules per cm.^{3}:

At 0° C. and 1.01323×10^6 bars,

$$N/V = 2.7048 \times 10^{19}$$

At 0° C. and 1×10^6 bars,

$$= 2.6696 \times 10^{19}$$

Boltzmann gas-constant,

$$R/N = k = 1.372 \times 10^{-16} \text{ erg/deg.}$$

Kinetic energy of a molecule at 0° C.,

$$= \tfrac{3}{2}k \times 273.1 = 5.621 \times 10^{-14} \text{ erg.}$$

Mass of hydrogen atom,

$$m_{\text{H}} = 1.008/N = 1.663 \times 10^{-24} \text{ gm.}$$

Ratio of charge to mass of electron,

$$e/m_0 = 1.769 \times 10^{7} \text{ e.m.u. gm.}^{-1}$$

Mass of electron,

$$m_0 = 8.995 \times 10^{-28} \text{ gm.}$$

Velocity of light,

$$c = 2.9986 \times 10^{10} \text{ cm. sec.}^{-1}$$

Constant of quantum theory (Planck constant),

$$h = 6.55 \times 10^{-27} \text{ erg sec.}$$

Constant of Einstein's photo-electric equation,

$$h/e = 1.372 \times 10^{-17} \text{ (e.g.s. units)}$$

Potential corresponding to frequency ν,

$$V = h\nu/e = 4.115 \times 10^{-15}\nu \text{ (volts)}$$

Potential corresponding to wavelength λ (Angstroms),

$$V = hc/\lambda e = 12{,}340/\lambda \text{ (volts)}$$

Constant in specific heat equations,

$$\beta = h/k = 4.774 \times 10^{-11} \text{ sec. deg.}$$

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